Lecture 5: Quenching and some other Accelerators

Plan

- the quench process
- decay times and temperature rise
- propagation of the resistive zone
- resistance growth and decay times
- quench protection schemes
- case study: LHC protection
- pictures of superconducting accelerators

the most likely cause of ***death*** *for a superconducting magnet*

Magnetic stored energy

Magnetic energy density

$$E = \frac{B^2}{2\mu_o}$$

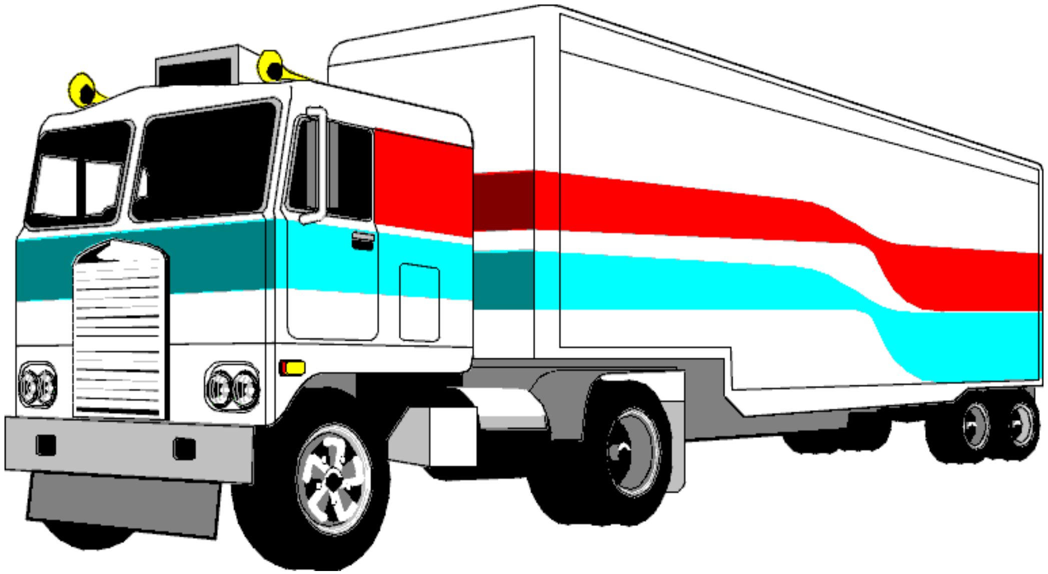
at 5T $\boldsymbol{E} = 10^7$ Joule.m^{-3}

at 10T $\boldsymbol{E} = 4 \times 10^7$ Joule.m^{-3}

LHC dipole magnet (twin apertures)

$\boldsymbol{E = \tfrac{1}{2} L I^2}$ $\boldsymbol{L} = 0.12$H $\boldsymbol{I} = 11.5$kA

E = 7.8 x 10^6 Joules

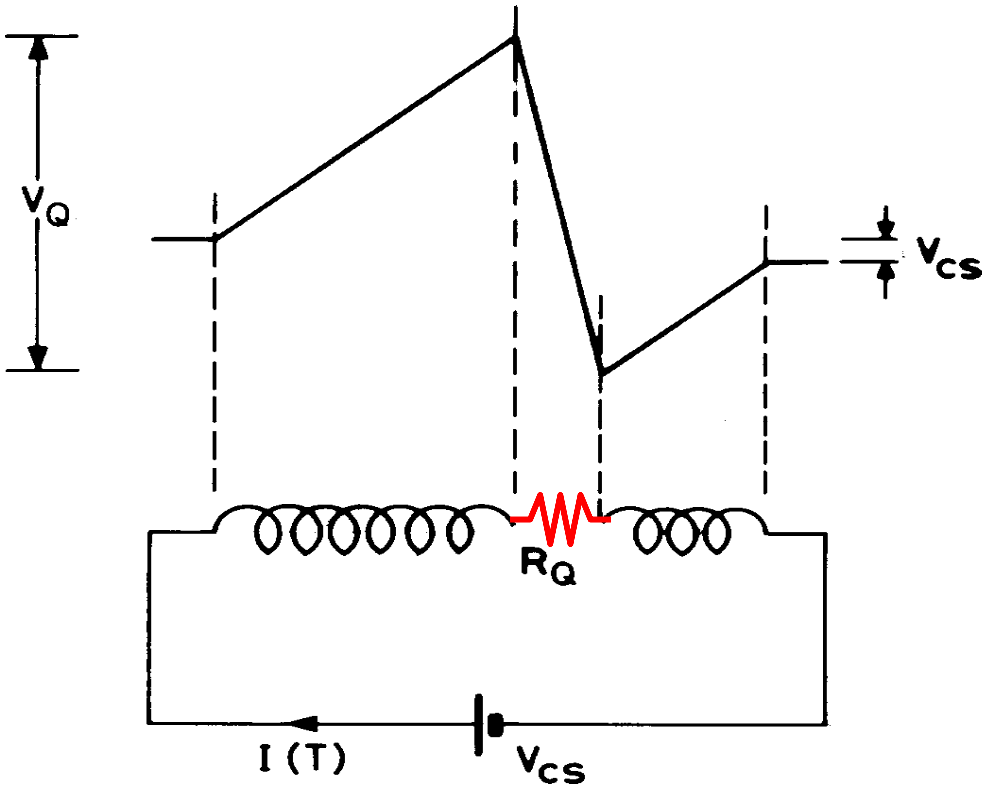


the magnet weighs 26 tonnes

so the magnetic stored energy is equivalent to the kinetic energy of:-

26 tonnes travelling at 88km/hr

The quench process



- resistive region starts somewhere in the winding at a **point**
  - this is the problem!
- it grows by thermal conduction
- stored energy $\frac{1}{2}LI^2$ of the magnet is dissipated as heat
- greatest integrated heat dissipation is at point where the quench starts
- internal voltages much greater than terminal voltage (= V_{cs} current supply)
- maximum temperature may be calculated from the current decay time via the U(θ) function (adiabatic approximation)

The temperature rise function U(θ)

or the 'fuse blowing' calculation
(adiabatic approximation)

$$J^2(T)\rho(\theta)dT = \gamma C(\theta)d\theta$$

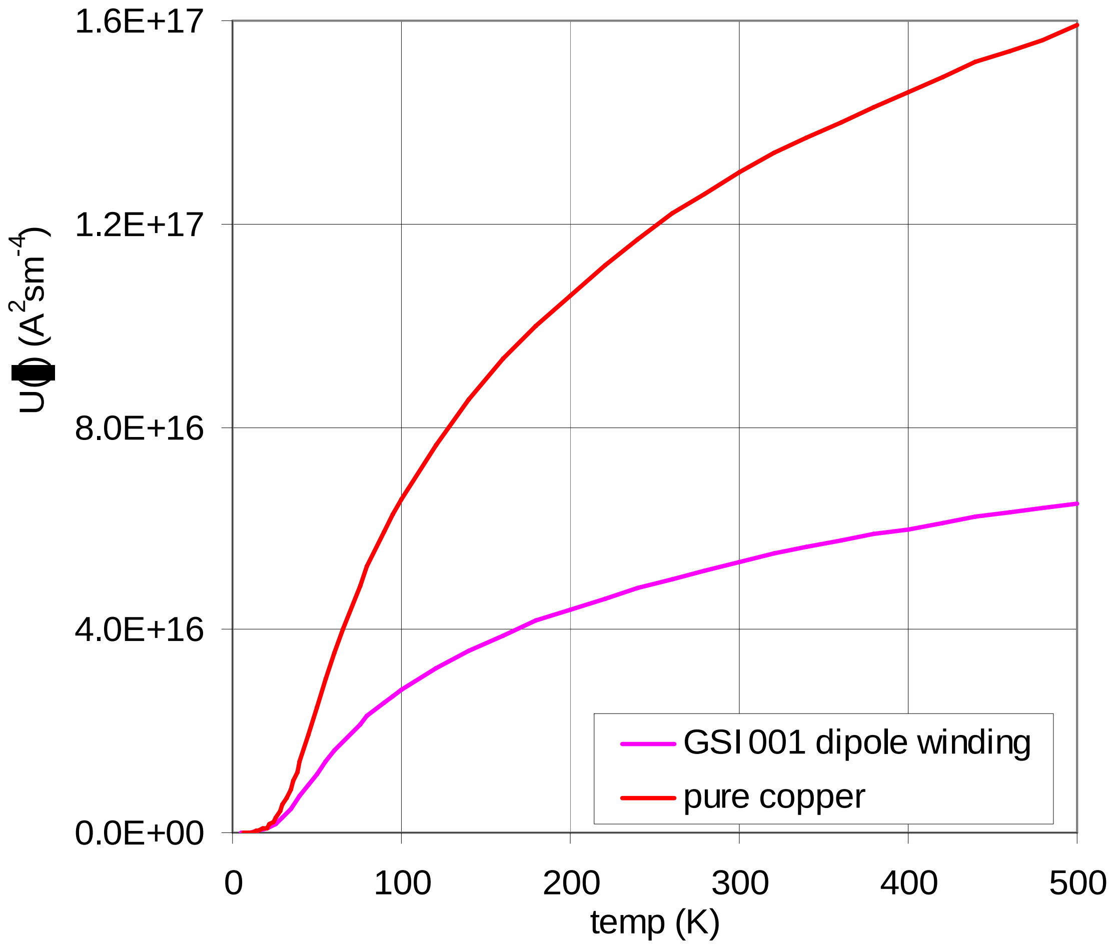
J(T) = overall current density,
T = time,
ρ(θ) = overall resistivity,
γ = density, *θ* = temperature,
C(θ) = specific heat,
T_Q = quench decay time.

$$\int_o^\infty J^2(T)\,dT = \int_{\theta o}^{\theta m} \frac{\gamma C(\theta)}{\rho(\theta)}\,d\theta$$

$$= U(\theta_m)$$

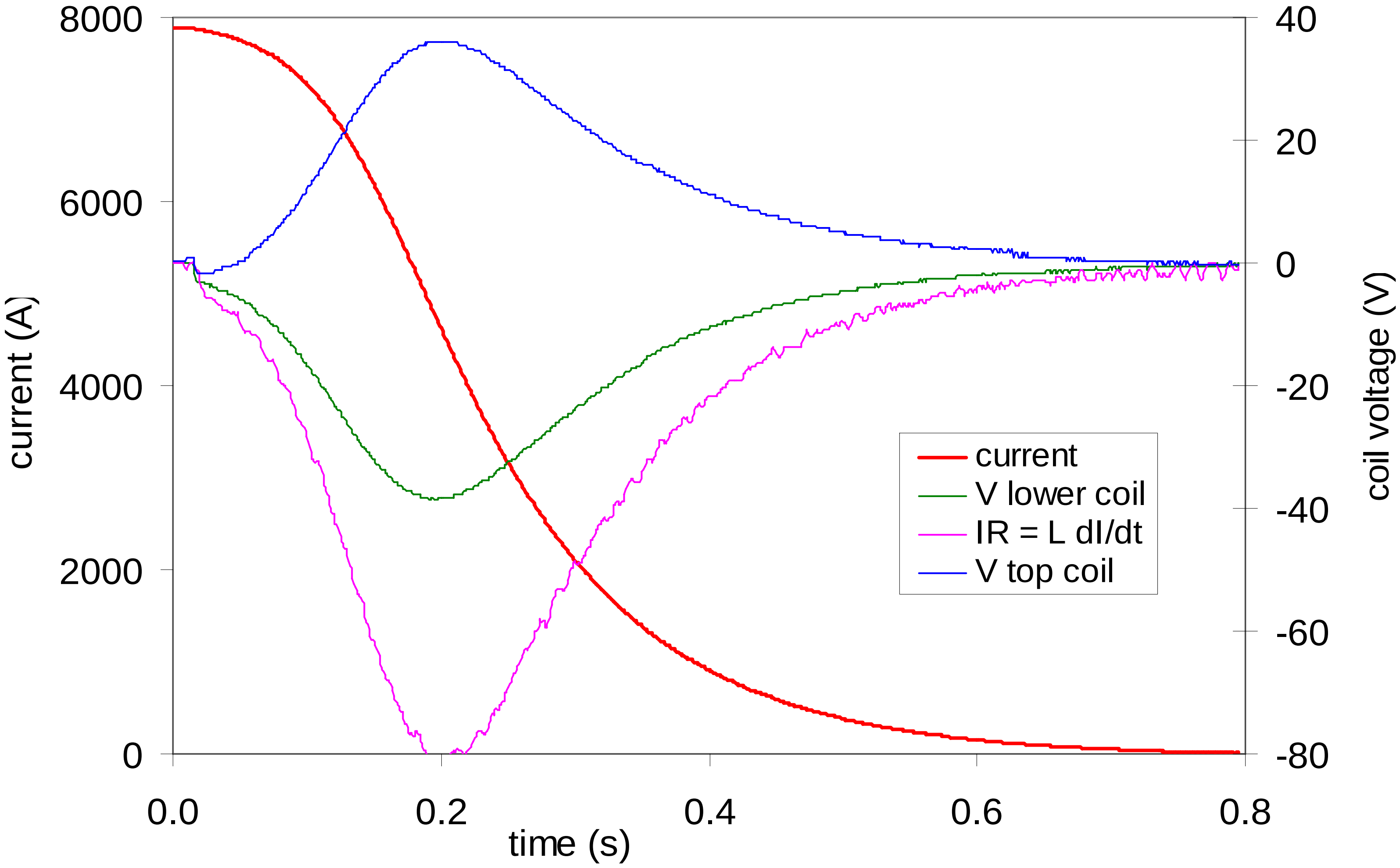
$$J_o^2 T_Q = U(\theta_m)$$

- GSI 001 dipole winding is 50% copper, 22% NbTi, 16% Kapton and 3% stainless steel



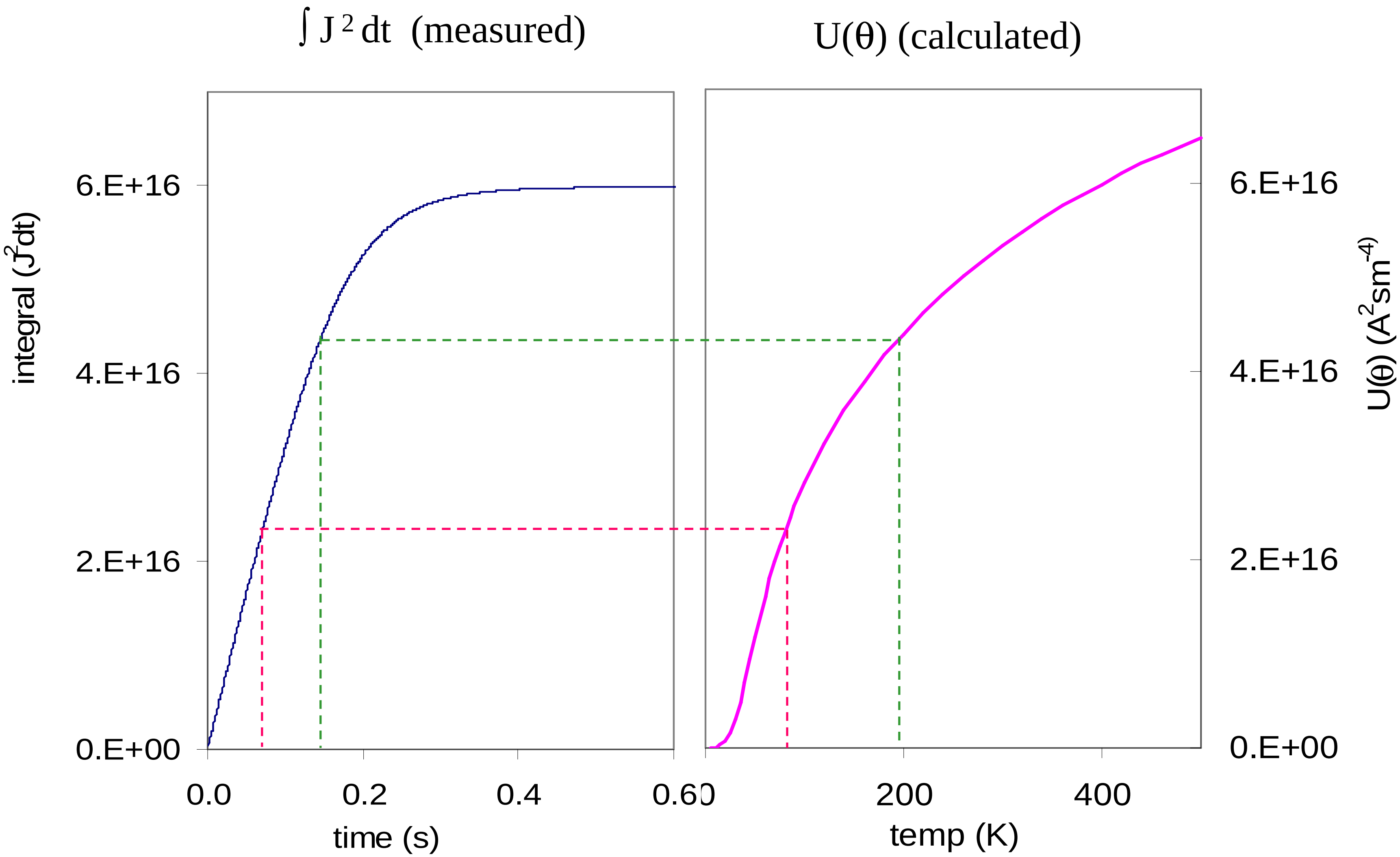
- NB always use **overall** current density

Measured current decay after a quench

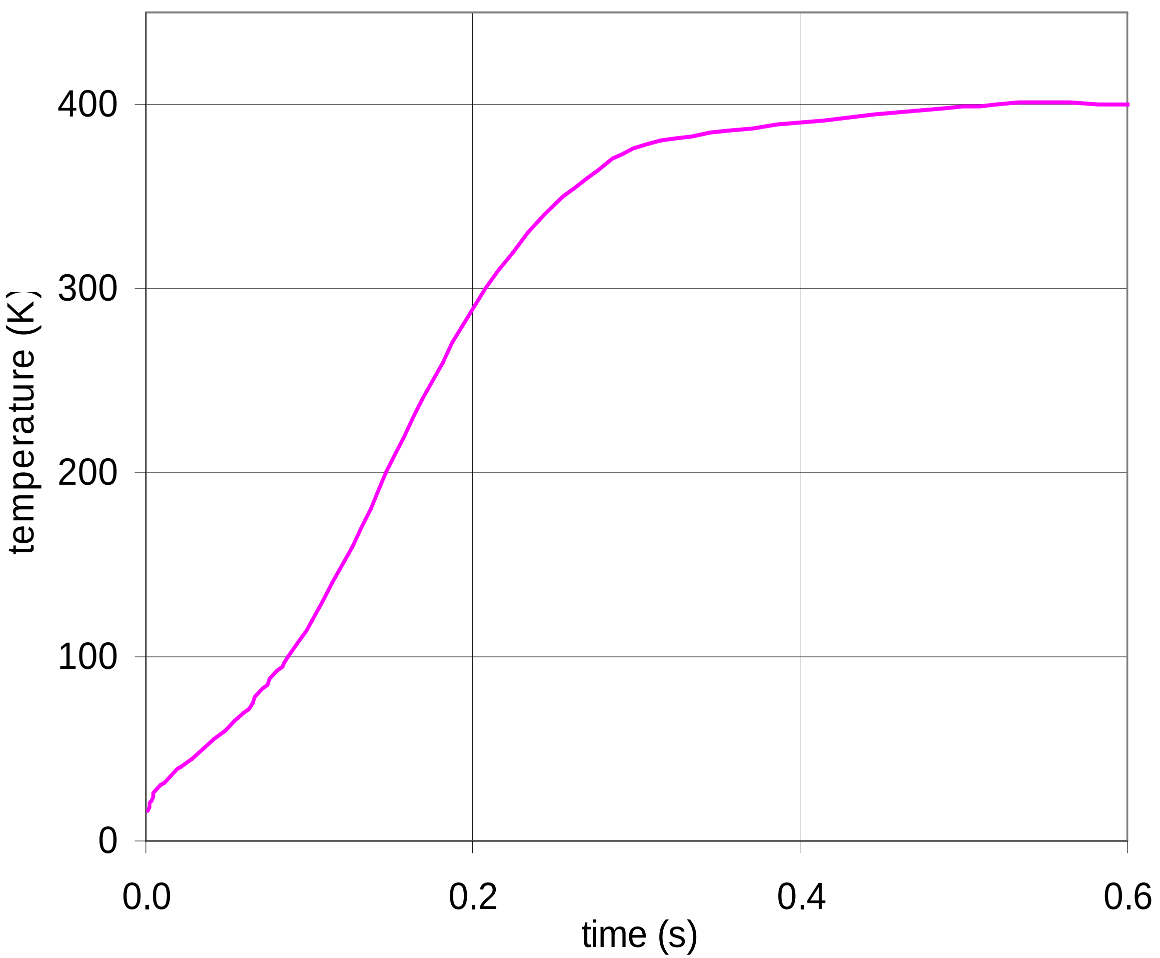


Dipole GSI001 measured at Brookhaven National Laboratory

Calculating the temperature rise from the current decay curve

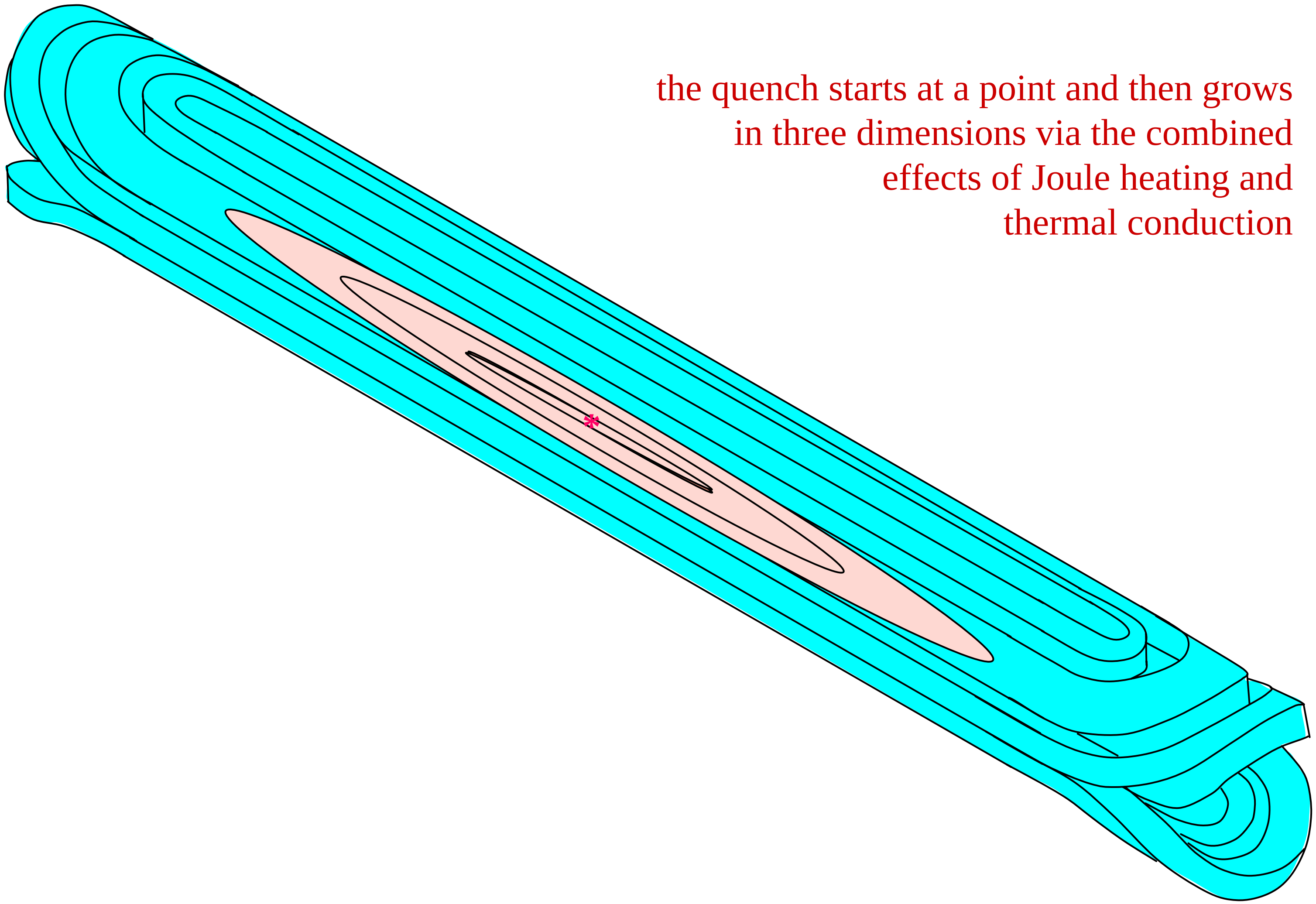


Calculated temperature



- calculate the U(θ) function from known materials properties
- measure the current decay profile
- calculate the maximum temperature rise at the point where quench starts
- we now know if the temperature rise is acceptable
  - but only after it has happened!
- need to calculate current decay curve before quenching

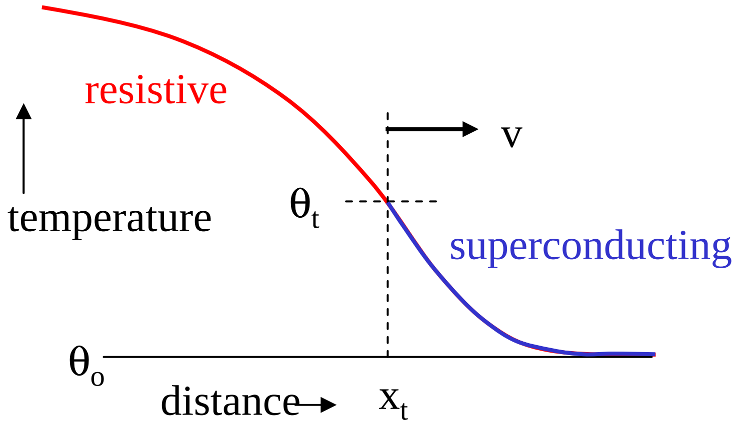
Growth of the resistive zone



the quench starts at a point and then grows in three dimensions via the combined effects of Joule heating and thermal conduction

Quench propagation velocity 1

- resistive zone starts at a point and spreads outwards
- the force driving it forward is the heat generation in the resistive zone, together with heat conduction along the wire
- write the heat conduction equations with resistive power generation $J^2\rho$ per unit volume in left hand region and $\rho = 0$ in right hand region.



$$\frac{\partial}{\partial x}\left(kA\frac{\partial\theta}{\partial x}\right)-\gamma CA\frac{\partial\theta}{\partial t}-hP(\theta-\theta_0)+J^2\rho A=0$$

where: k = thermal conductivity, A = area occupied by a single turn, γ = density, C = specific heat, h = heat transfer coefficient, P = cooled perimeter, ρ = resistivity, θ_o = base temperature

Note: all parameters are averaged over A the cross section occupied by one turn

assume x_t moves to the right at velocity v and take a new coordinate $\varepsilon = x - x_t = x - vt$

$$\frac{d^2\theta}{d\varepsilon^2}+\frac{v\gamma C}{k}\frac{d\theta}{d\varepsilon}-\frac{hP}{kA}(\theta-\theta_0)+\frac{J^2\rho}{k}=0$$

Quench propagation velocity 2

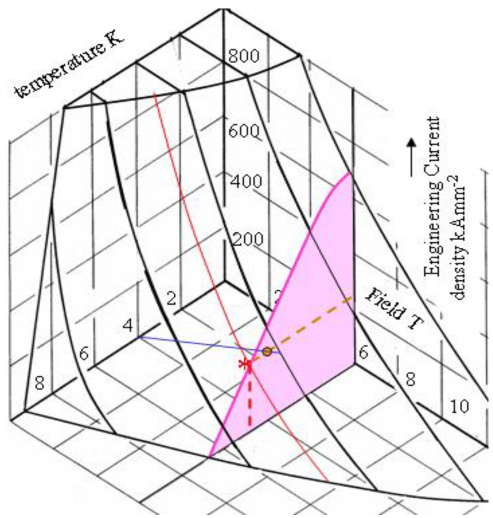
when $h = 0$, the solution for θ which gives a continuous join between left and right sides at θ_t gives the ***adiabatic propagation velocity***

$$v_{ad} = \frac{J}{\gamma C}\left\{\frac{\rho k}{\theta_t - \theta_0}\right\}^{\frac{1}{2}} = \frac{J}{\gamma C}\left\{\frac{L_o \theta_t}{\theta_t - \theta_0}\right\}^{\frac{1}{2}}$$

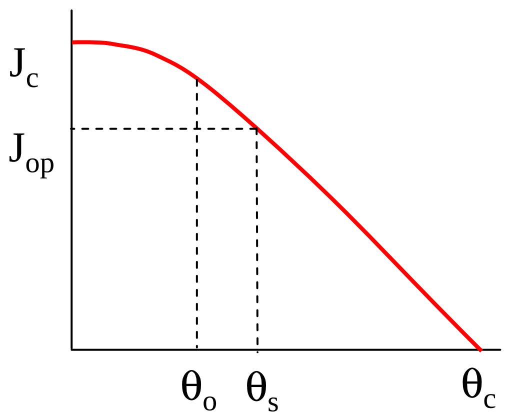
recap Wiedemann Franz Law $\rho(\theta).k(\theta) = L_o\theta$

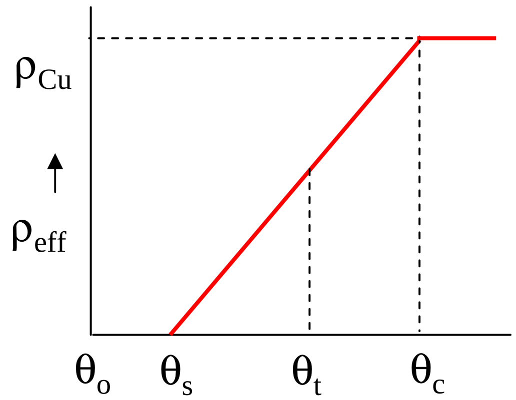
what to say about θ_t ?

- in a single superconductor it is just θ_c
- but in a practical filamentary composite wire the current transfers progressively to the copper



- current sharing temperature $\theta_s = \theta_o + margin$
- zero current in copper below θ_s all current in copper above θ_s
- take a mean transition temperature $\theta_s = (\theta_s + \theta_c)/2$





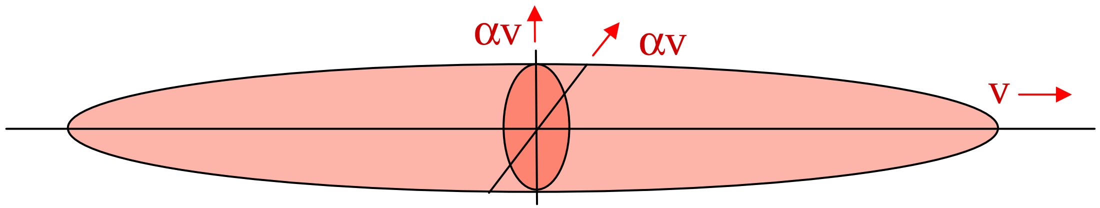
Quench propagation velocity 3

the resistive zone also propagates sideways through the inter-turn insulation (much more slowly) calculation is similar and the velocity ratio α is:

$$\alpha = \frac{v_{trans}}{v_{long}} = \left\{ \frac{k_{trans}}{k_{long}} \right\}^{\frac{1}{2}}$$

Typical values $v_{ad} = 5 - 20\ \mathrm{ms}^{-1}$ $\alpha = 0.01 - 0.03$

so the resistive zone advances in the form of an ellipsoid, with its long dimension along the wire



Some corrections for a better approximation

- because C varies so strongly with temperature, it is better to calculate an averaged C from the enthalpy change

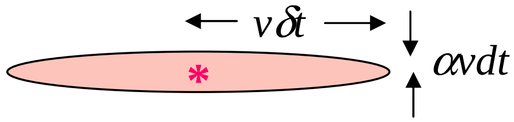
$$C_{av}(\theta_g, \theta_c) = \frac{H(\theta_c) - H(\theta_g)}{(\theta_c - \theta_g)}$$

- heat diffuses slowly into the insulation, so its heat capacity should be excluded from the averaged heat capacity when calculating longitudinal velocity - but not transverse velocity
- if the winding is porous to liquid helium (usual in accelerator magnets) need to include a time dependent heat transfer term
- can approximate all the above, but for a really good answer must solve (numerically) the three dimensional heat diffusion equation or, even better, measure it!

Computation of resistance growth and current decay

start resistive zone 1

in time δt zone 1 grows $v.dt$ longitudinally and $\alpha.v.dt$ transversely

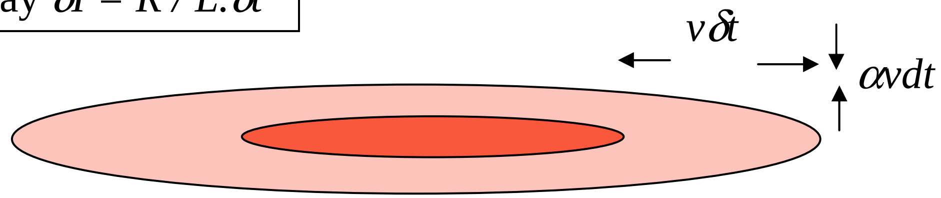


temperature of zone grows by $\delta\theta_1 = J^2 \rho(\theta_1)\delta\tau / \gamma C(\theta_1)$

resistivity of zone 1 is $\rho(\theta_1)$

calculate resistance and hence current decay $\delta I = R / L.\delta t$

in time δt add zone n:
$v.\delta t$ longitudinal and $\alpha.v.\delta t$ transverse



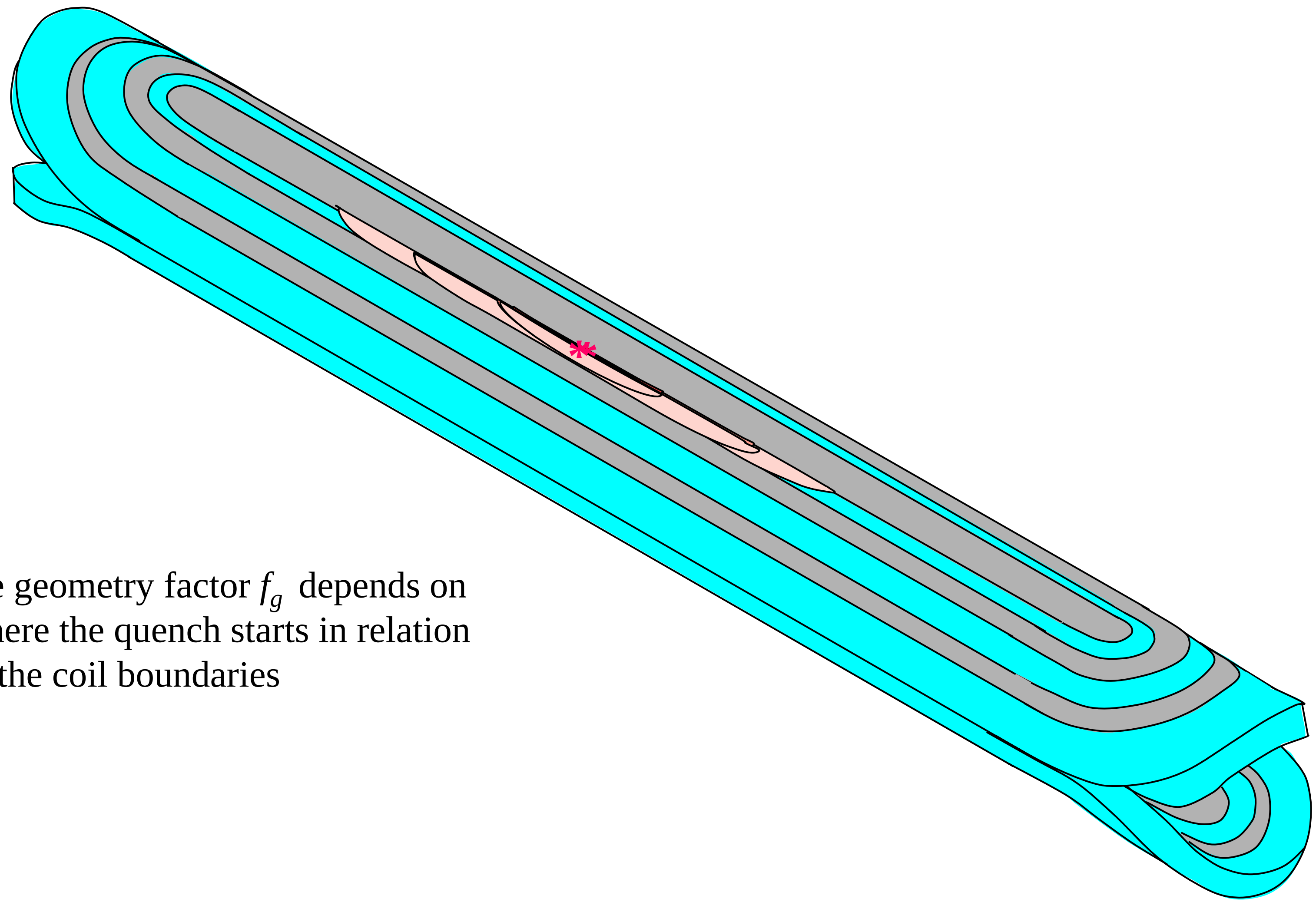
temperature of each zone grows by $\delta\theta_1 = J^2\rho(\theta_1)\delta t / \gamma C(\theta_1)$ $\delta\theta_2 = J^2\rho(\theta_2)\delta t / \gamma C(\theta_2)$ $\delta\theta_n = J^2\rho(\theta_1)dt / \gamma C(\theta_n)$

resistivity of each zone is $\rho(\theta_1)$ $\rho(\theta_2)$ $\rho(\theta_n)$ resistance $r_1 = \rho(\theta_1) * f_{g1}$ (geom factor) $r_2 = \rho(\theta_2) * f_{g2}$ $r_n = \rho(\theta_n) * f_{gn}$

calculate total resistance $R = \sum r_1 + r_2 + r_{n..}$ and hence current decay $\delta I = (I\,R/L)\delta t$

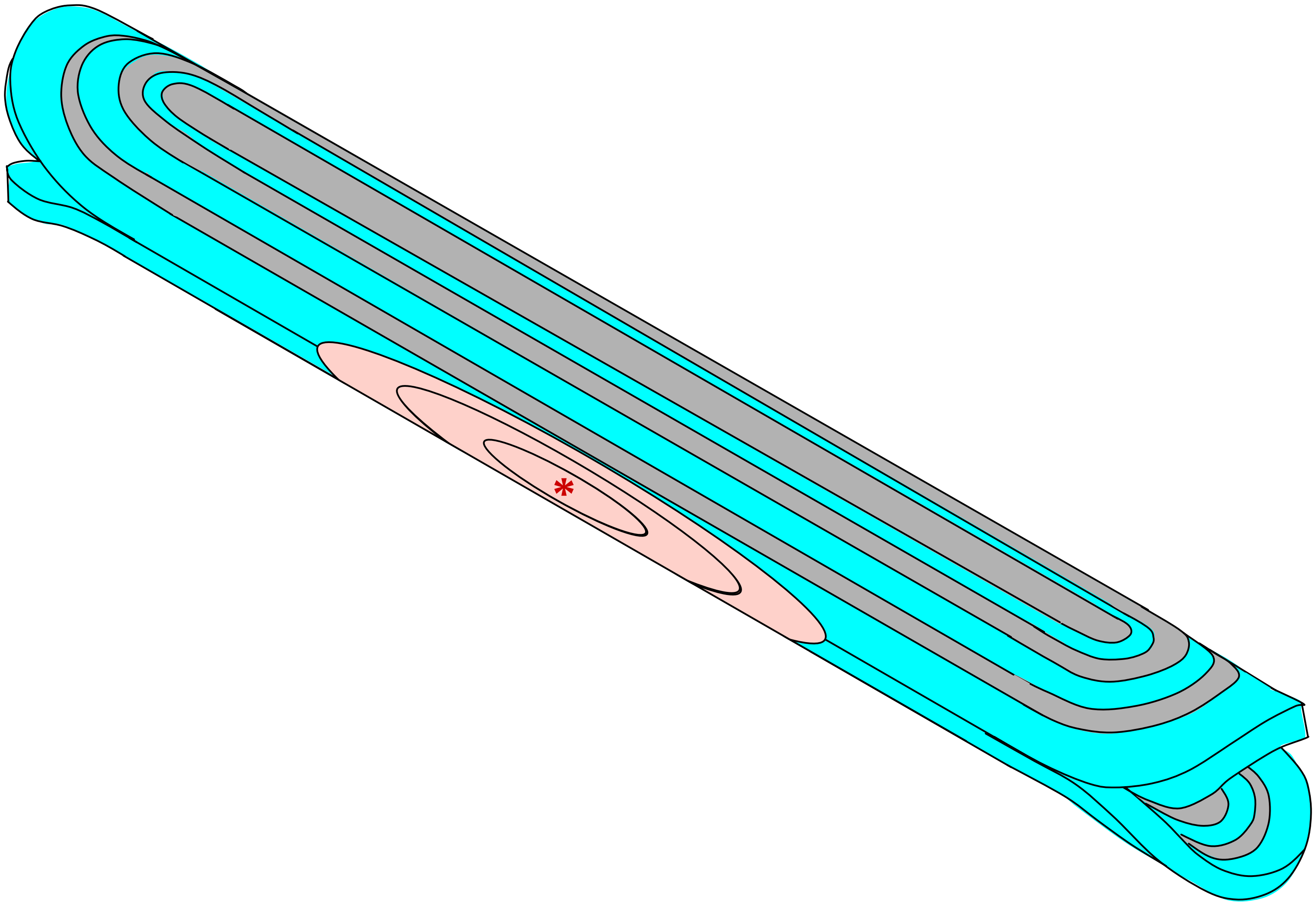
when $I \Rightarrow 0$ stop

Quench starts in the pole region

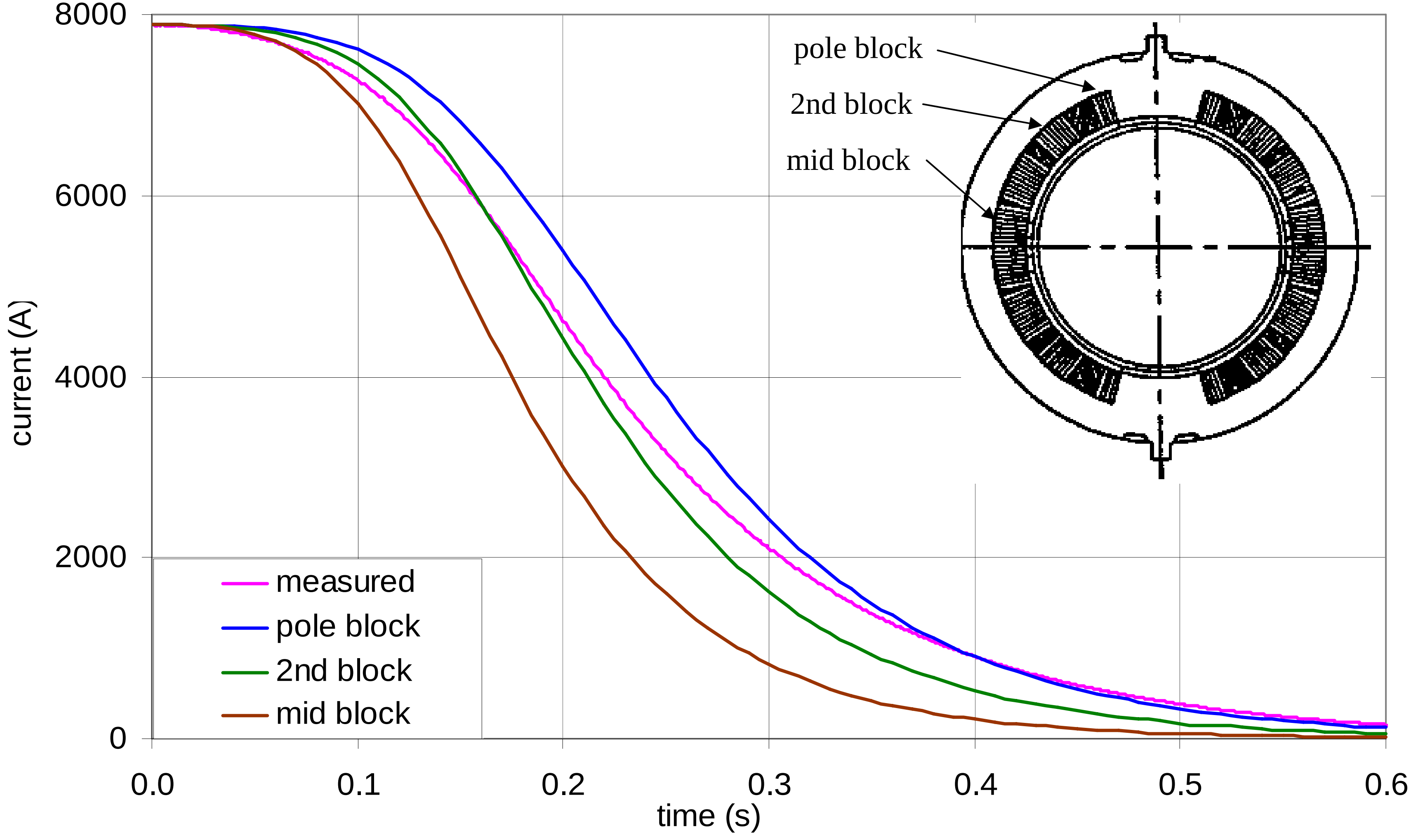


the geometry factor f_g depends on where the quench starts in relation to the coil boundaries

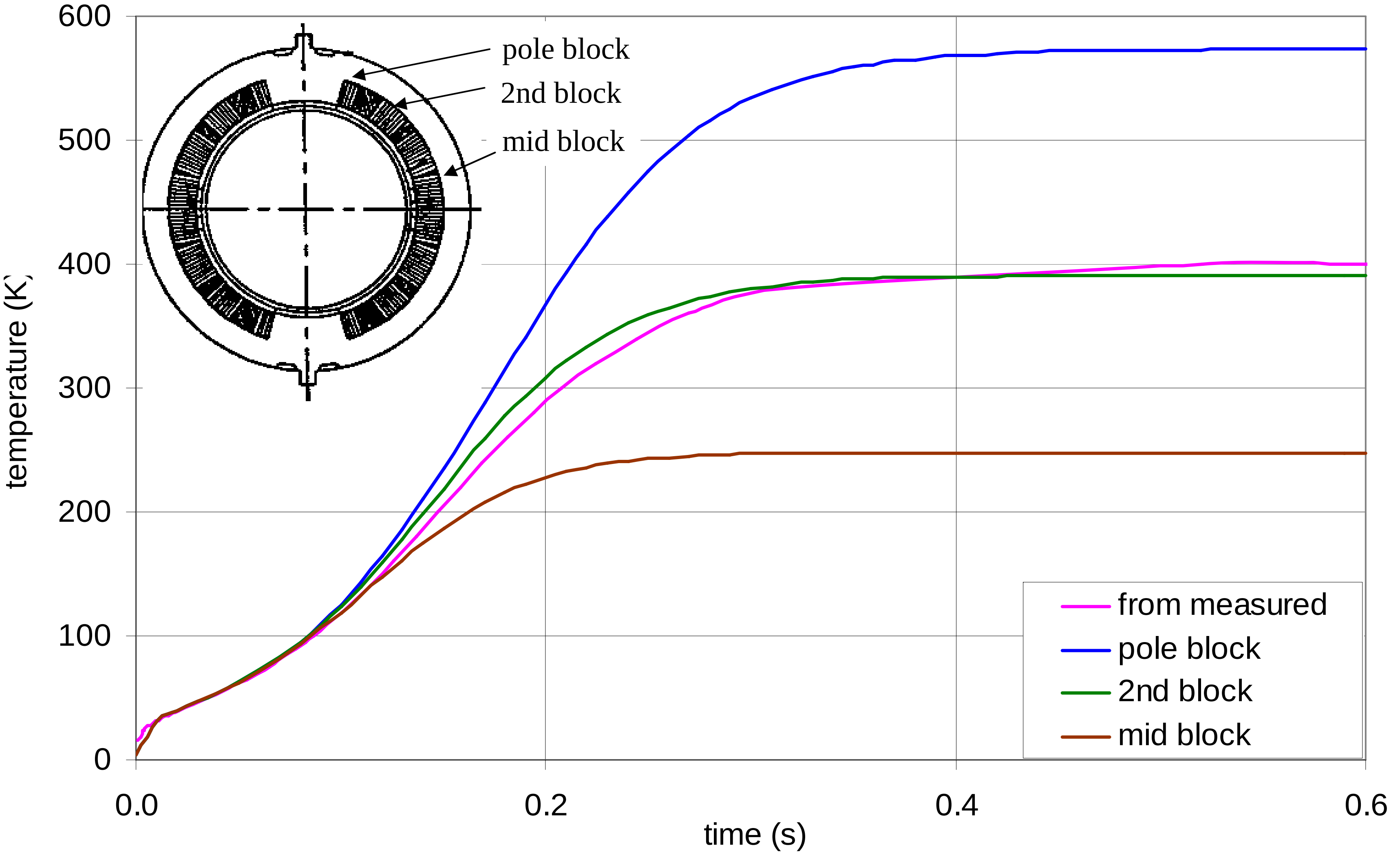
Quench starts in the mid plane



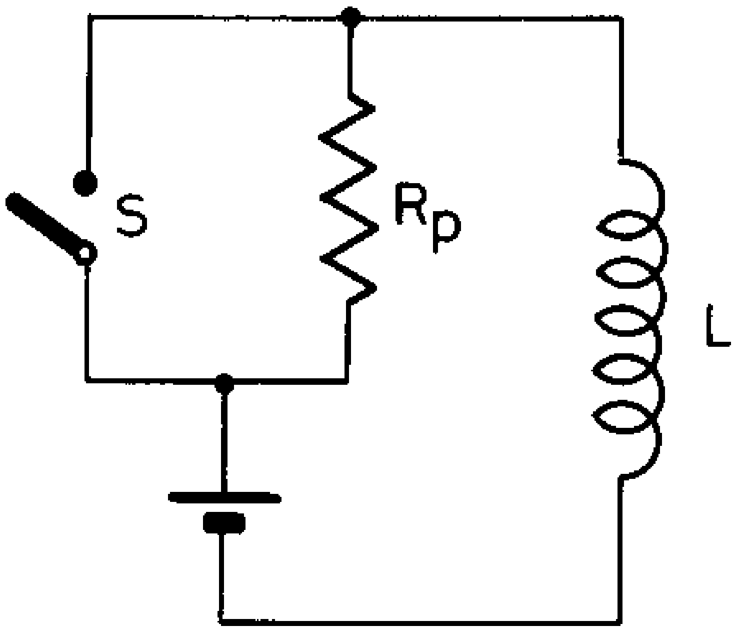
Computer simulation of quench (dipole GSI001)



Computer simulation of quench temperature rise



Methods of quench protection:
1) external dump resistor



- detect the quench electronically
- open an external circuit breaker
- force the current to decay with a time constant

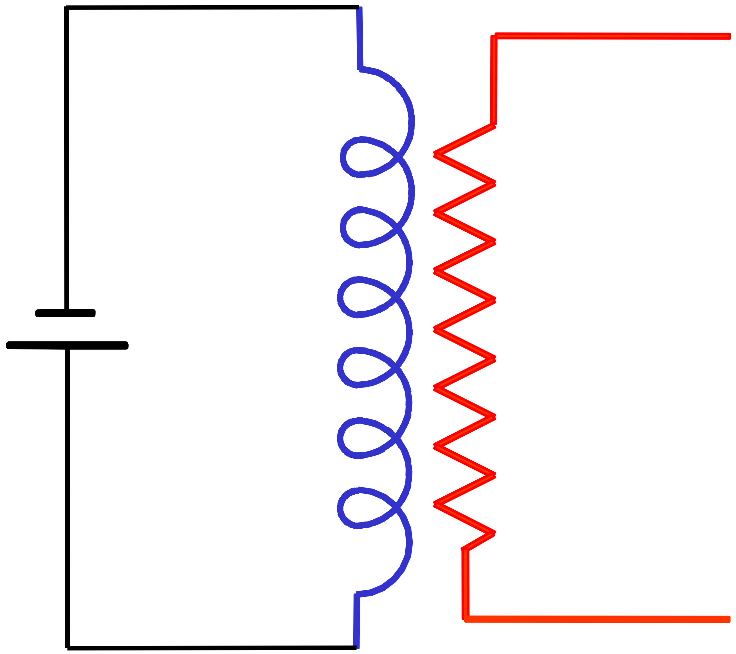
$$I = I_o e^{-\frac{t}{\tau}} \qquad \text{where} \qquad \tau = \frac{L}{R_p}$$

- calculate θ_{max} from

$$J_o^2 \tau = U(\theta_m)$$

Note: circuit breaker must be able to open at full current against a voltage $V = I.R_p$ (expensive)

Methods of quench protection:
2) quench back heater

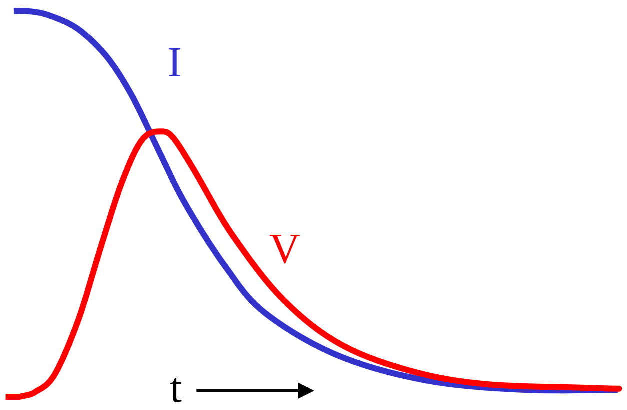


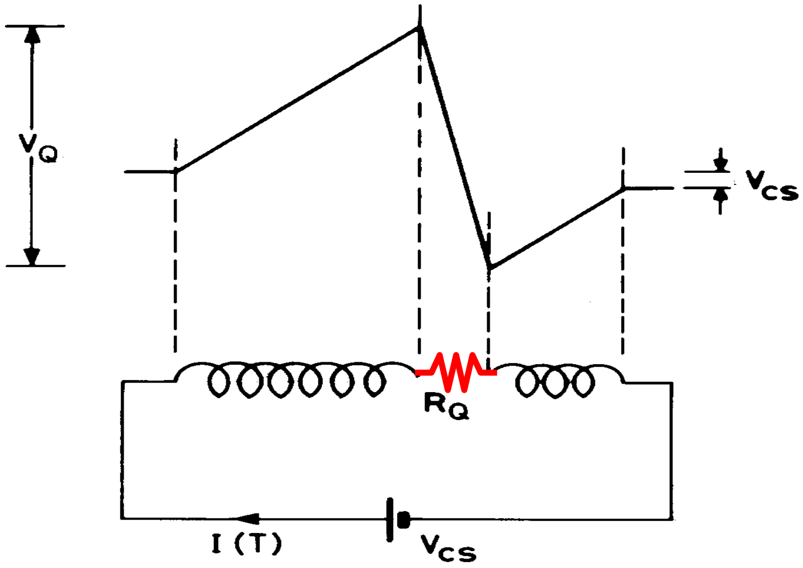
- detect the quench electronically
- power a heater in good thermal contact with the winding
- this quenches other regions of the magnet, effectively forcing the normal zone to grow more rapidly
  $\Rightarrow$ higher resistance
  $\Rightarrow$ shorter decay time
  $\Rightarrow$ lower temperature rise at the hot spot

Note: usually pulse the heater by a capacitor, the high voltages involved raise a conflict between:-
- ***good themal contact***
- ***good electrical insulation***

method most commonly used in accelerator magnets ✓

Methods of quench protection:
3) quench detection (a)



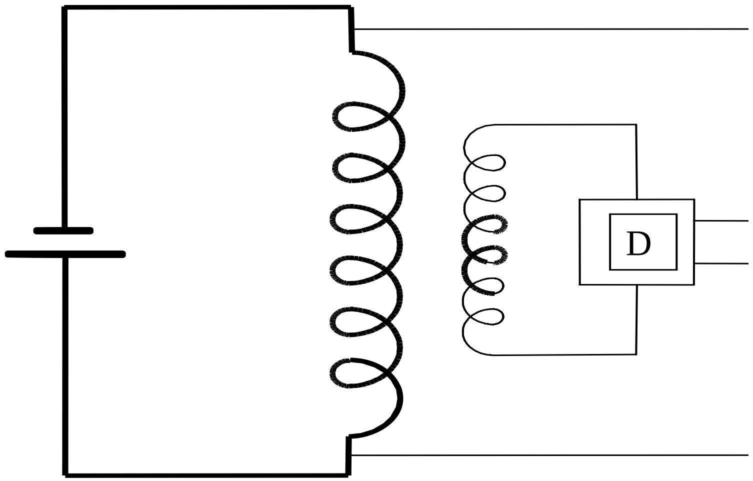


internal voltage after quench $V = IR_Q = -L\frac{dI}{dt} + V_{cs}$

- not much happens in the early stages - small $dI/dt \Rightarrow$ small V
- but important to act soon if we are to reduce T_Q significantly
- so must detect small voltage
- superconducting magnets have large inductance $\Rightarrow$ large voltages during charging
- detector must reject $V = L\,dI/dt$ and pick up $V = IR$
- detector must also withstand high voltage - **as must the insulation**

Methods of quench protection:
3) quench detection (b)

i) Mutual inductance



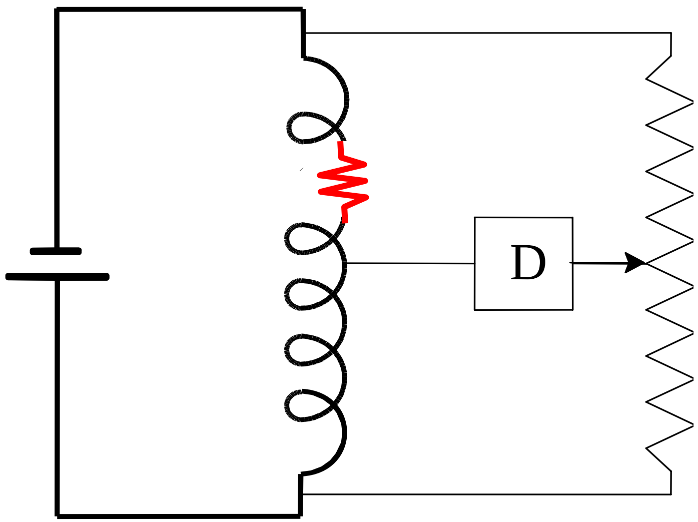
detector subtracts voltages to give

$$V = L\frac{di}{dt} + IR_Q - M\frac{di}{dt}$$

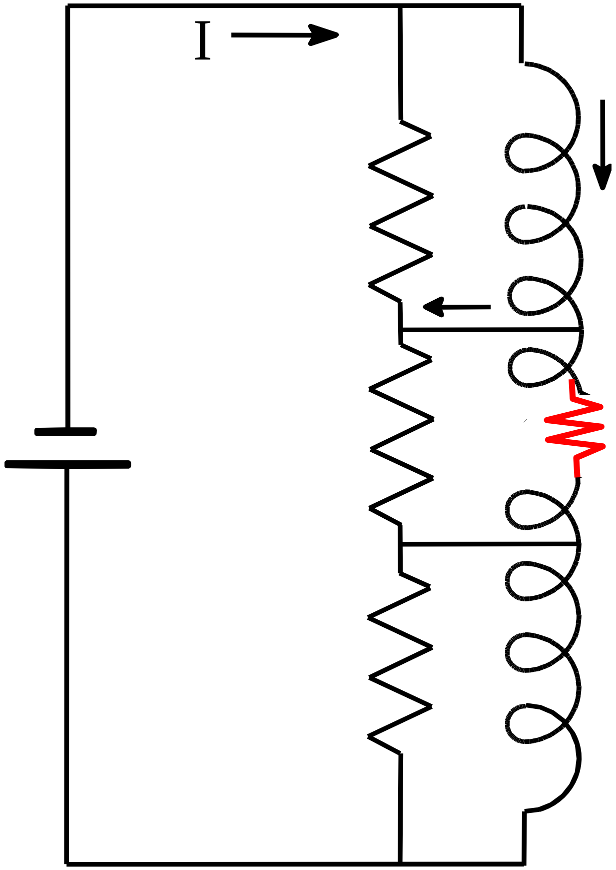
- adjust detector to effectively make $L = M$
- M can be a toroid linking the current supply bus, but must be linear - no iron!

ii) Balanced potentiometer

- adjust for balance when not quenched
- unbalance of resistive zone seen as voltage across detector D
- if you worry about symmetrical quenches connect a second detector at a different point



Methods of quench protection:
4) Subdivision

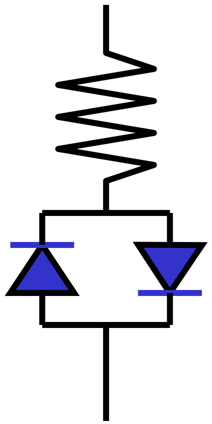


- resistor chain across magnet - cold in cryostat
- current from rest of magnet can by-pass the resistive section
- effective inductance of the quenched section is reduced

  ⇒ reduced decay time

  ⇒ reduced temperature rise
- current in rest of magnet increased by mutual inductance effects

  ⇒ quench initiation in other regions
- often use cold diodes to avoid shunting magnet when charging it
- diodes only conduct (forwards) when voltage rises to quench levels
- connect diodes 'back to back' so they can conduct (above threshold) in either direction

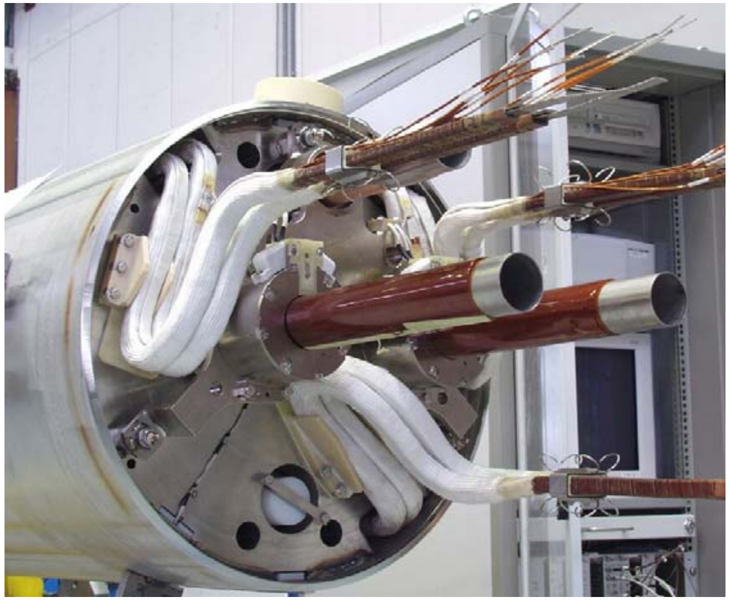


Case study: LHC dipole protection

It's difficult! - the main challenges are:

1) Series connection of many magnets

- In each octant, 154 dipoles are connected in series. If one magnet quenches, the combined inductance of the others will try to maintain the current. Result is that the stored energy of all 154 magnets will be fed into the magnet which has quenched $\Rightarrow$ vaporization of that magnet!.
- **Solution 1**: put cold diodes across the terminals of each magnet. In normal operation, the diodes do not conduct - so that the magnets all track accurately. At quench, the diodes of the quenched magnet conduct so that the octant current by-passes that magnet.



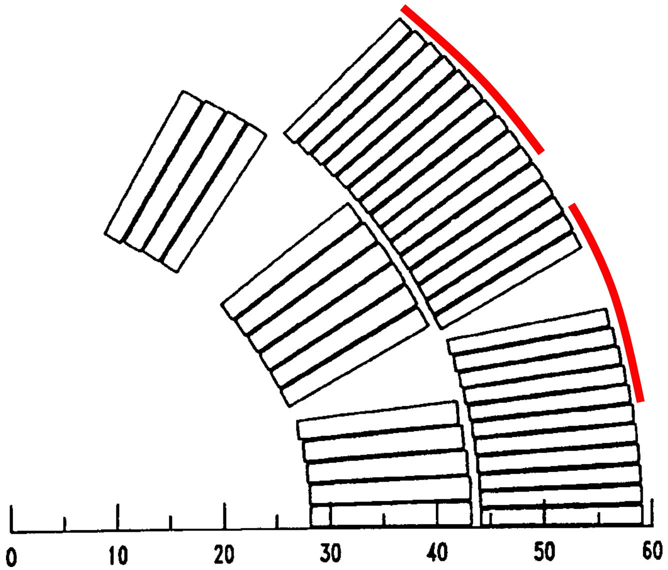
- **Solution 2:** open a circuit breaker onto a dump resistor (several tonnes) so that the current in the octant is reduced to zero in ~ 100 secs.

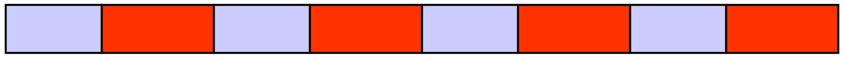
2) High current density, high stored energy and long length

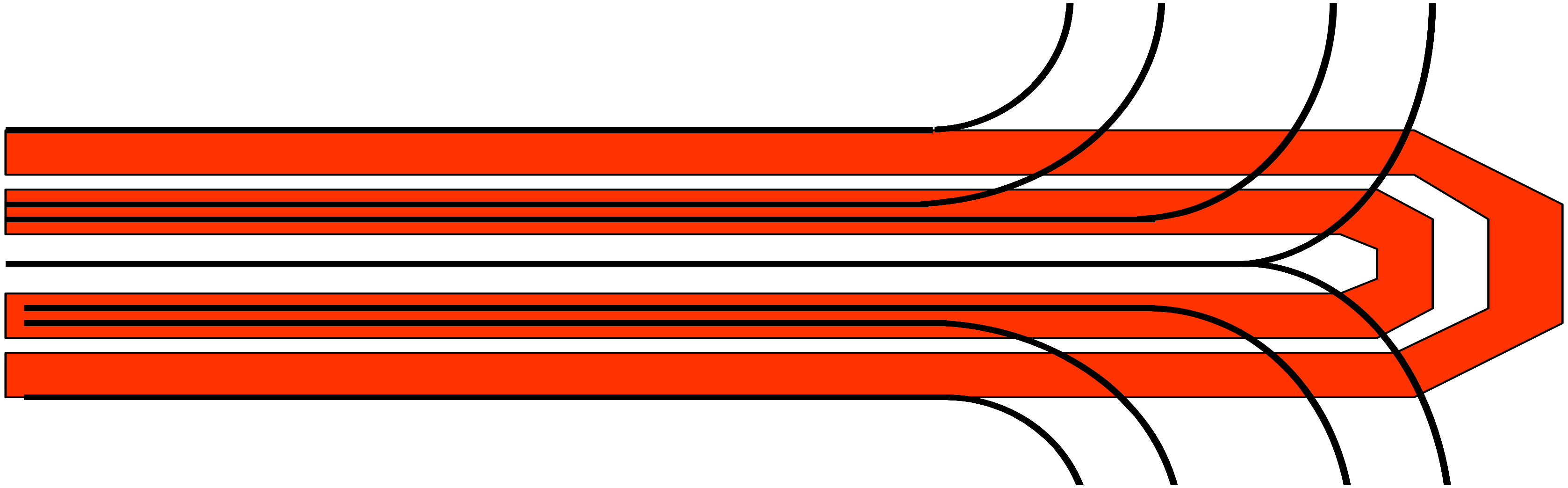
- As a result of these factors, the individual magnets are not self protecting. If they were to quench alone or with the by-pass diode, they would still burn out.
- **Solution 3:** Quench heaters on top and bottom halves of every magnet.

LHC quench-back heaters

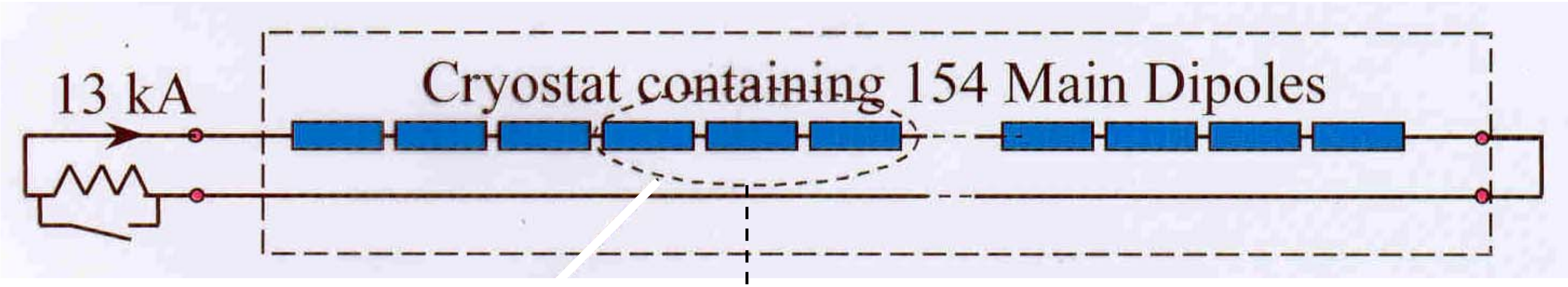
- stainless steel foil 15mm x 25 µm glued to outer surface of winding
- insulated by Kapton
- pulsed by capacitor 2 x 3.3 mF at 400 V = 500 J
- quench delay - at rated current = 30msec
  - at 60% of rated current = 50msec
- copper plated 'stripes' to reduce resistance



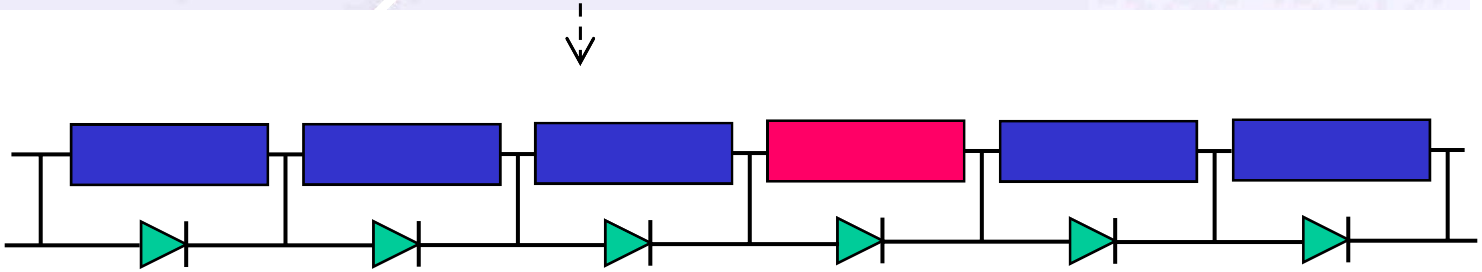




LHC power supply circuit for one octant



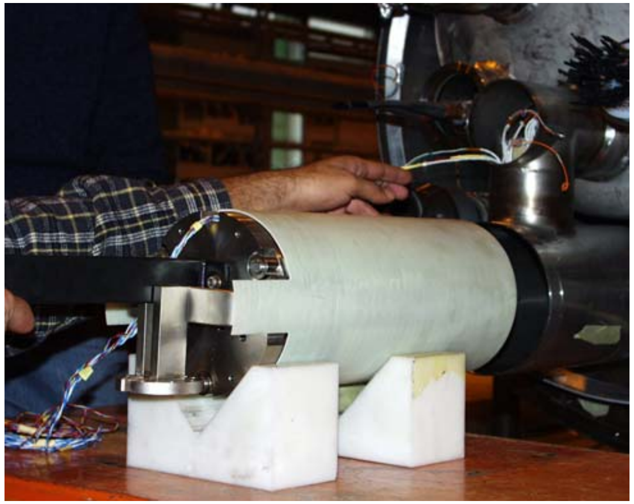
circuit
breaker



- diodes allow the octant current to by-pass the magnet which has quenched
- circuit breaker reduces to octant current to zero with a time constant of 100 sec
- initial voltage across breaker = 2000V
- stored energy of the octant = 1.33GJ

Diodes to by-pass the main ring current

Installing the cold diode package on the end of an LHC dipole

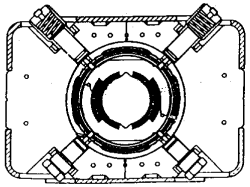


Quenching: concluding remarks

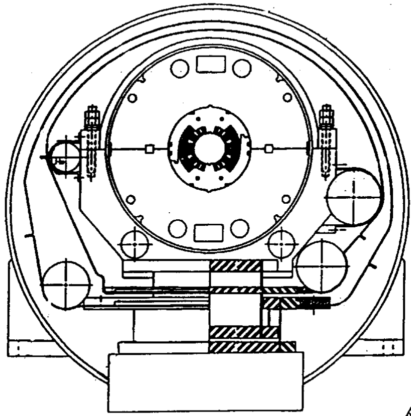
- magnets store large amounts of energy - during a quench this energy gets dumped in the winding
  ⇒ intense heating (J ~ fuse blowing) ⇒ possible death of magnet
- temperature rise and internal voltage can be calculated from the current decay time
- computer modelling of the quench process gives an estimate of decay time
  – but must decide where the quench starts
- if temperature rise is too much, must use a protection scheme
- active quench protection schemes use quench heaters or an external circuit breaker
  - need a quench detection circuit which must reject $L\,dI/dt$ and be **100%** reliable
- passive quench protection schemes are less effective because V grows so slowly
  - but are 100% reliable
- protection of accelerator magnets is made more difficult by series connection
  - all the other magnets feed their energy into the one that quenches
- for accelerator magnets use by-pass diodes and quench heaters
- remember the quench when designing the magnet insulation

always do the quench calculations before testing the magnet ✓

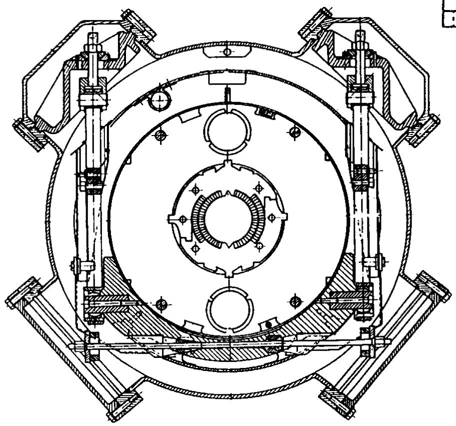
The world's superconducting accelerator dipoles



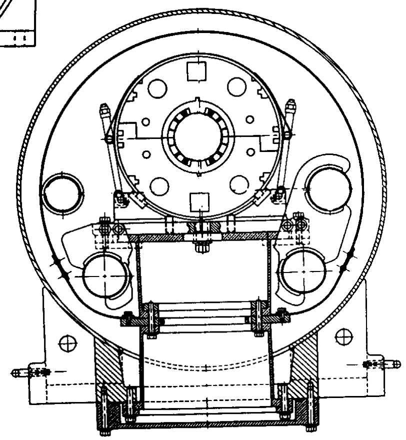
Tevatron



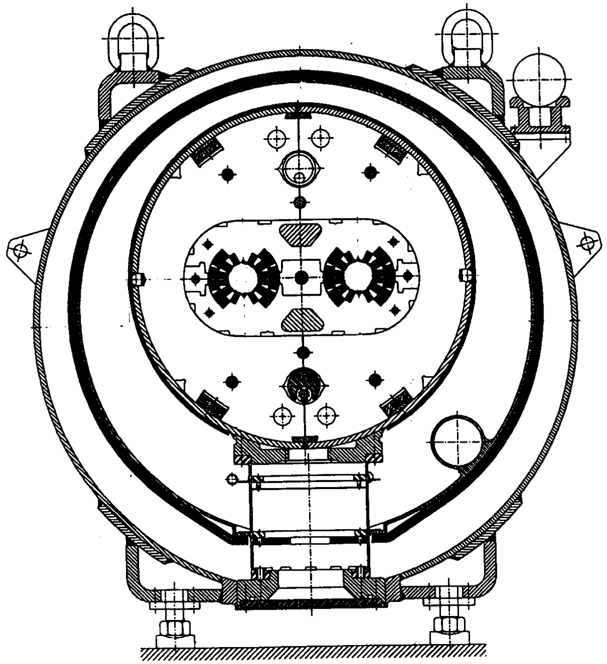
SSC



HERA



RHIC

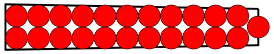
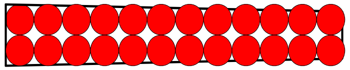
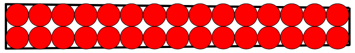
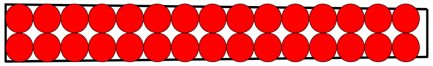
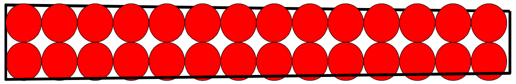
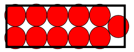


LHC

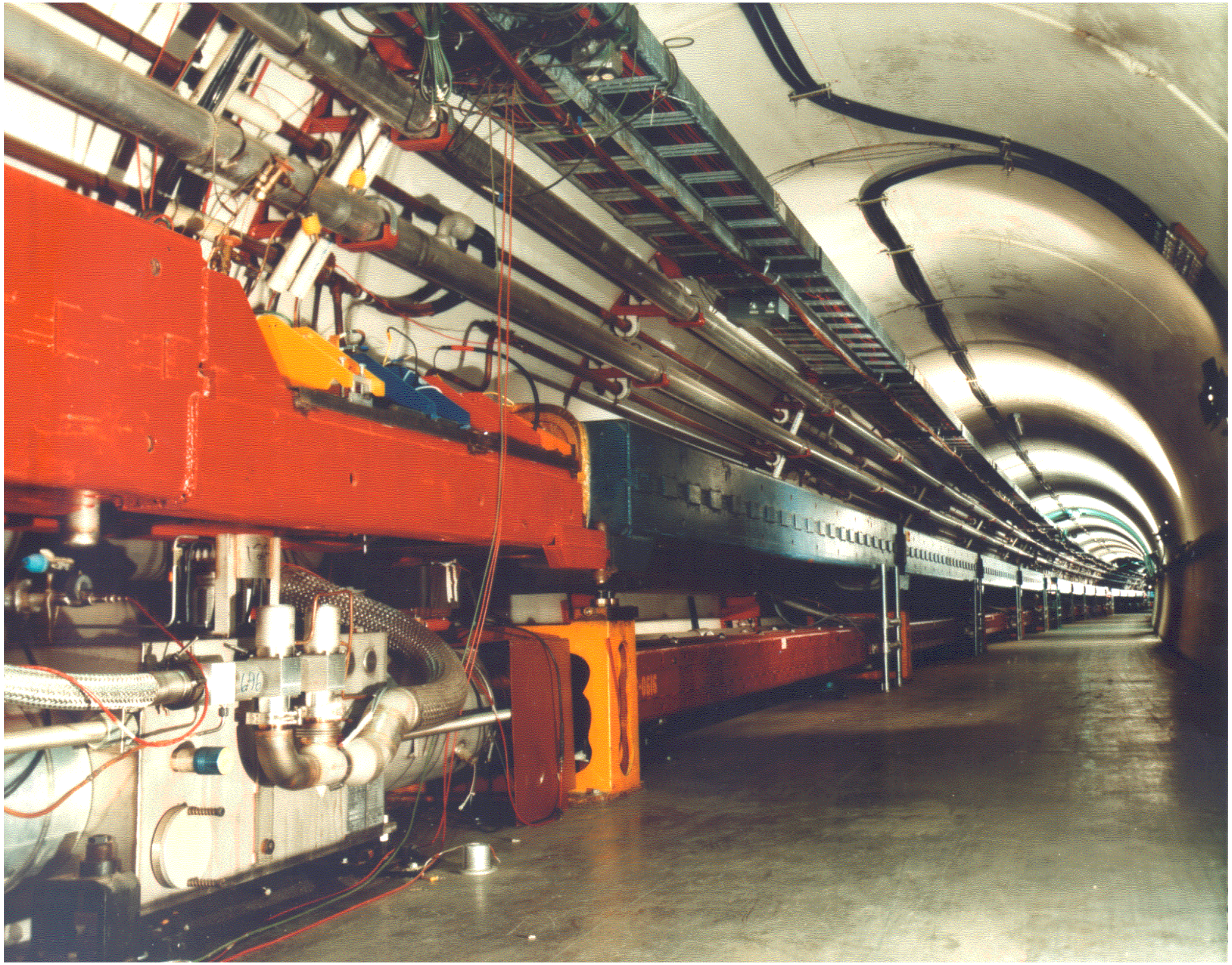
Key parameters of dipoles

		Tevatron	HERA	SSC	RHIC	LHC	Helios
max energy	GeV	950	820	20,000 x 2	250 x 2	7,000 x 2	0.7
max field	T	4.4	4.68	6.79	3.46	8.36	4.5
max current	kA	4.4.	5.03	6.5	5.09	11.5	1.04
injection field	T	0.66	0.23	0.68	0.4	0.58	0.64
aperture	mm	76	75	50	80	56	58
length	m	6.1	8.8	15.2	9.4	14.2	1.6
operating temperature	K	4.6	4.5	4.35	4.6	1.9	4.5
number off		774	422	3972	396	1232	2

Superconducting cables of the world's accelerators

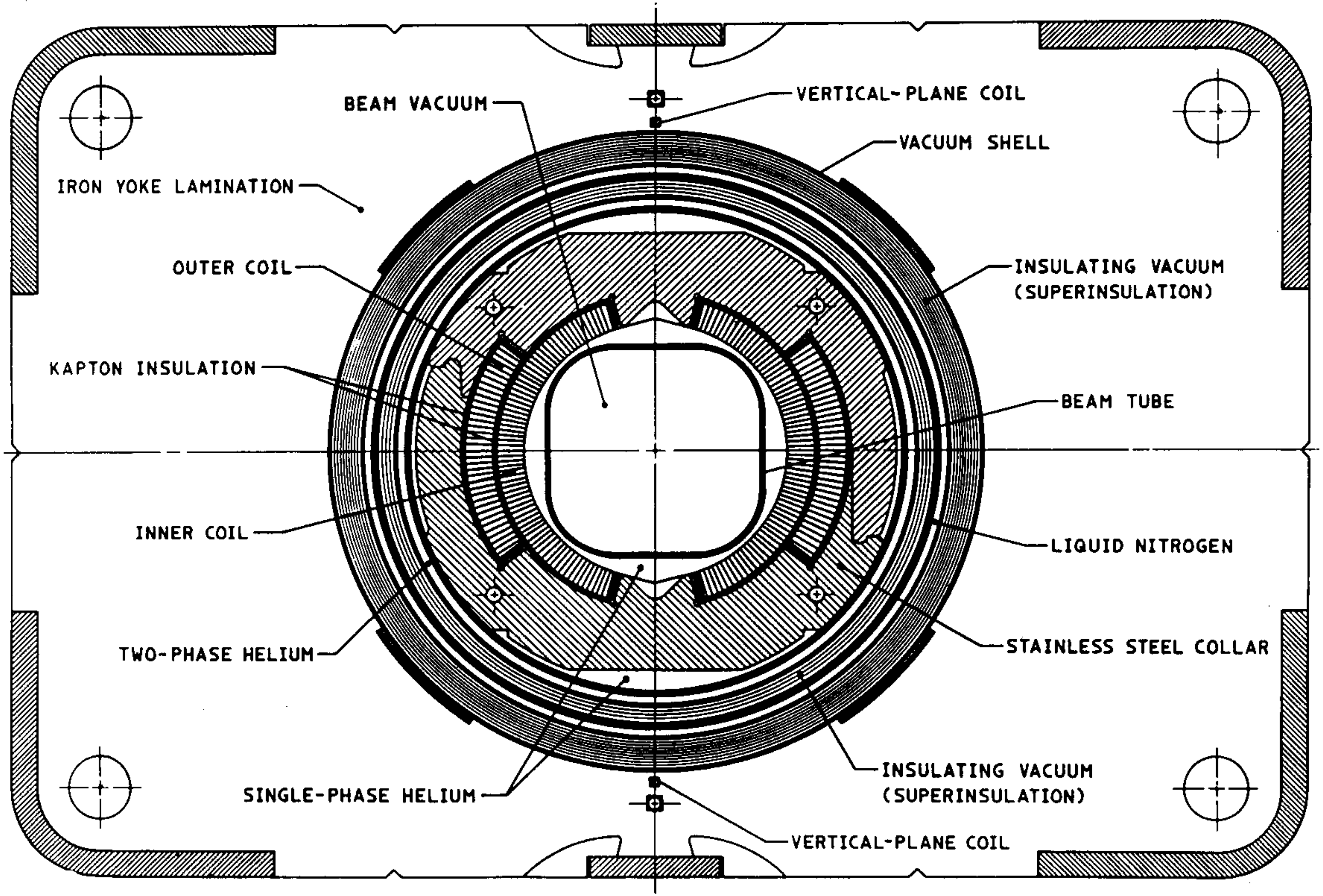
accelerator	cable	filament dia µm	cable width mm	twist pitch mm	wire surface
Tevatron		6	7.8	66	zebra
HERA		14-16	10	95	SnAg
RHIC		6	9.7	73	copper
SSC		6	12.3	79	copper
LHC		7	15	115	SnAg pre-ox
Helios		8.5	3.2	40	copper

The Fermilab Tevatron

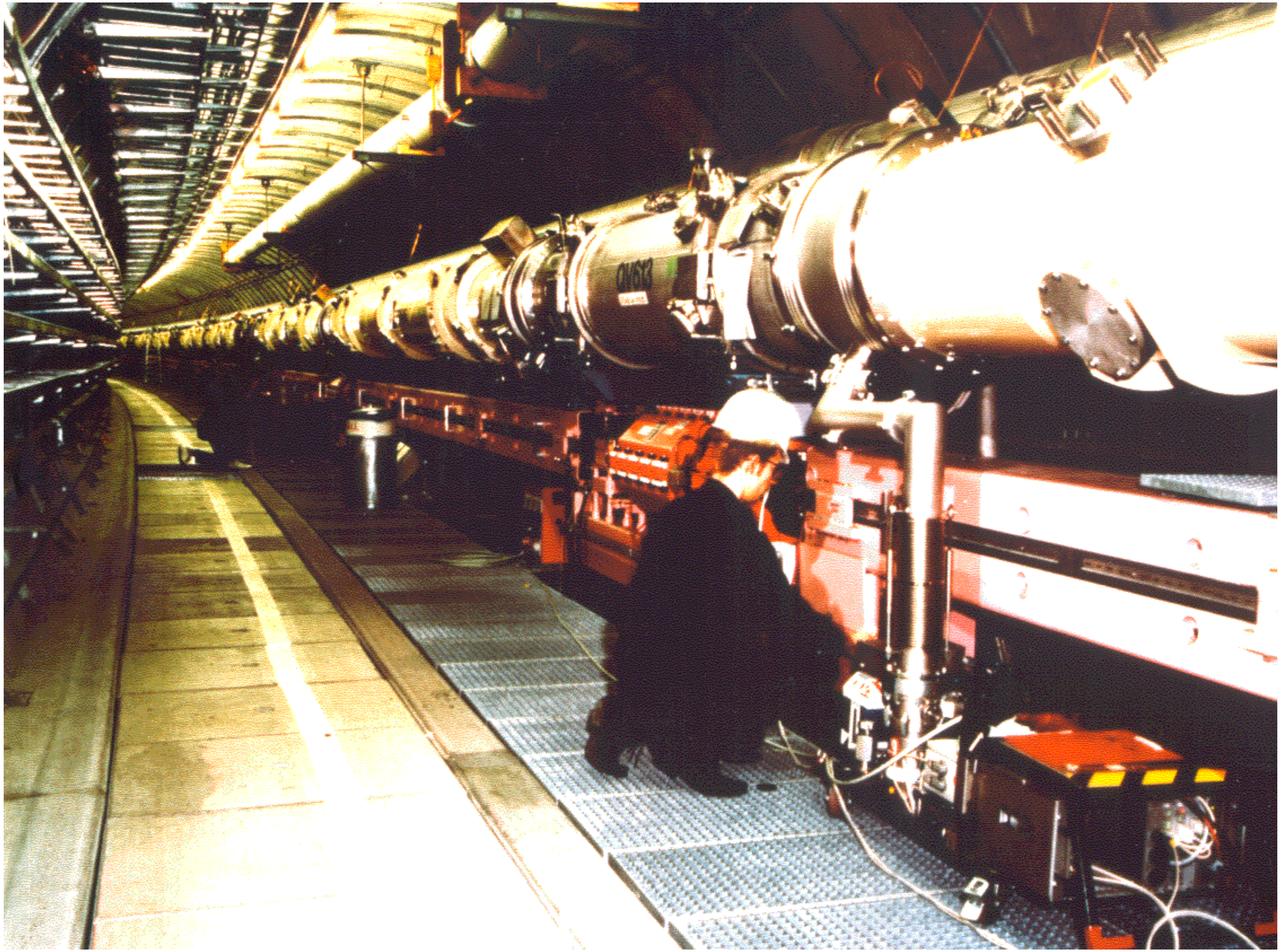


the world's first superconducting accelerator

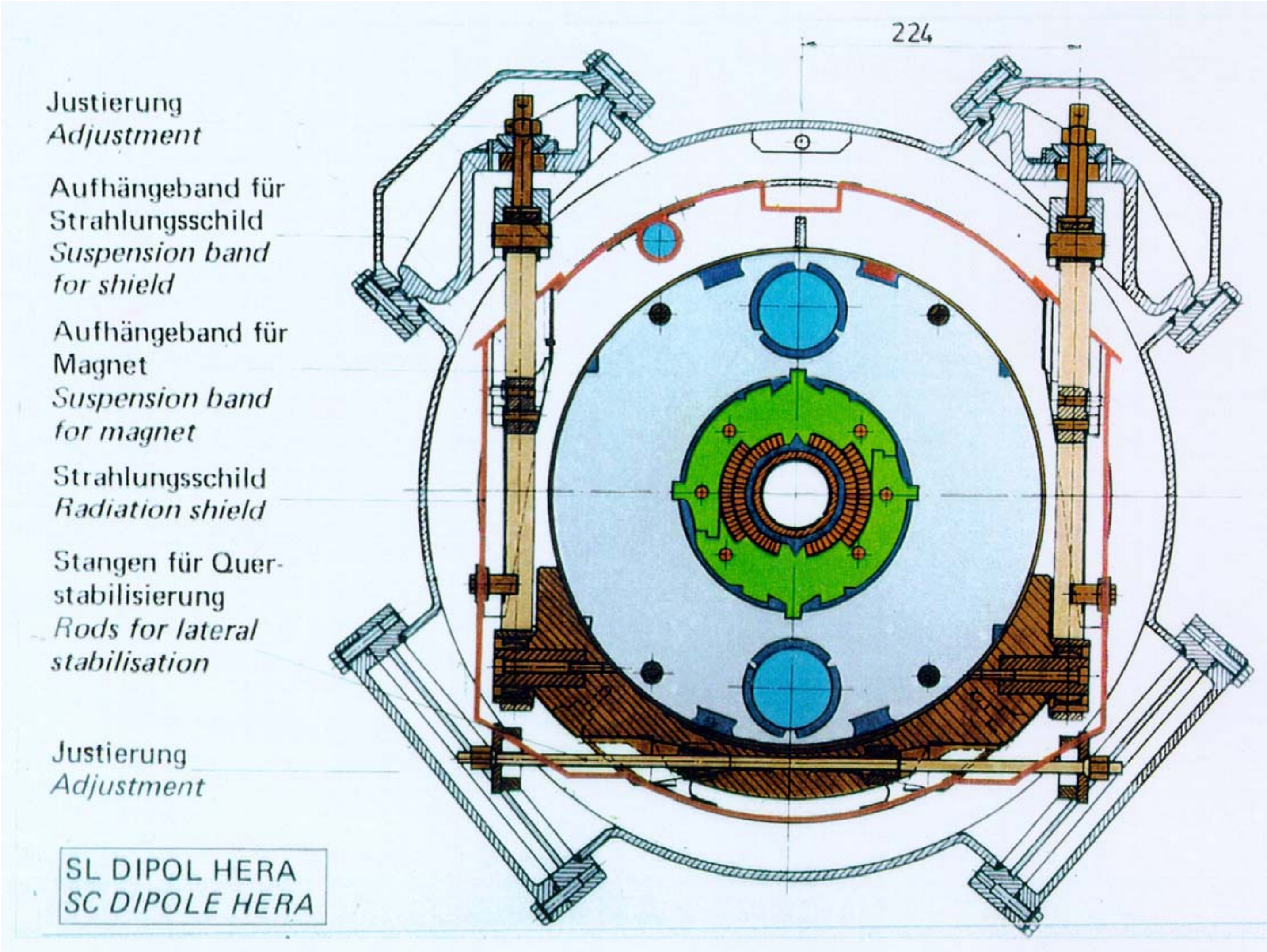
Tevatron dipole



Hera

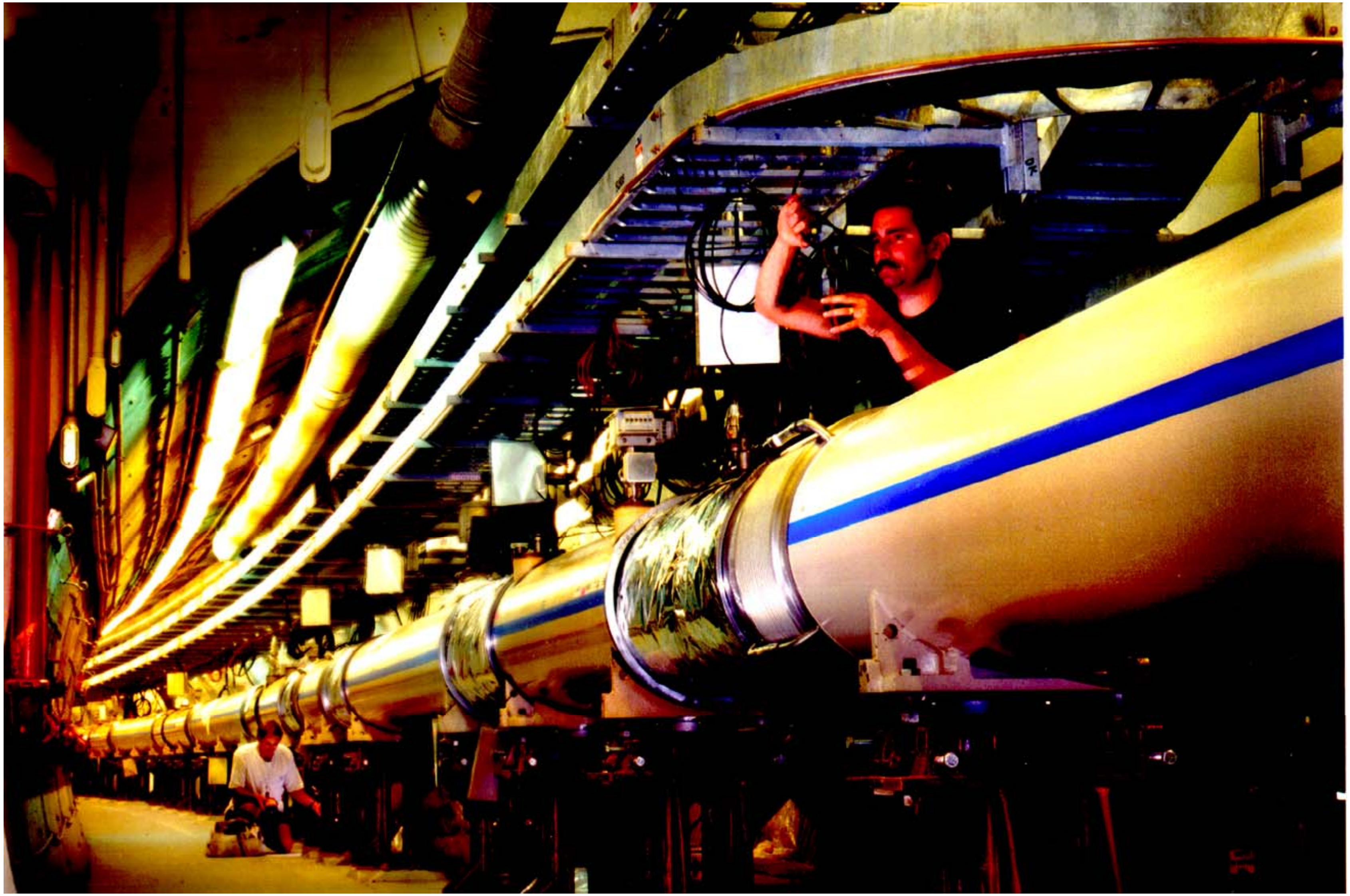


Hera dipole

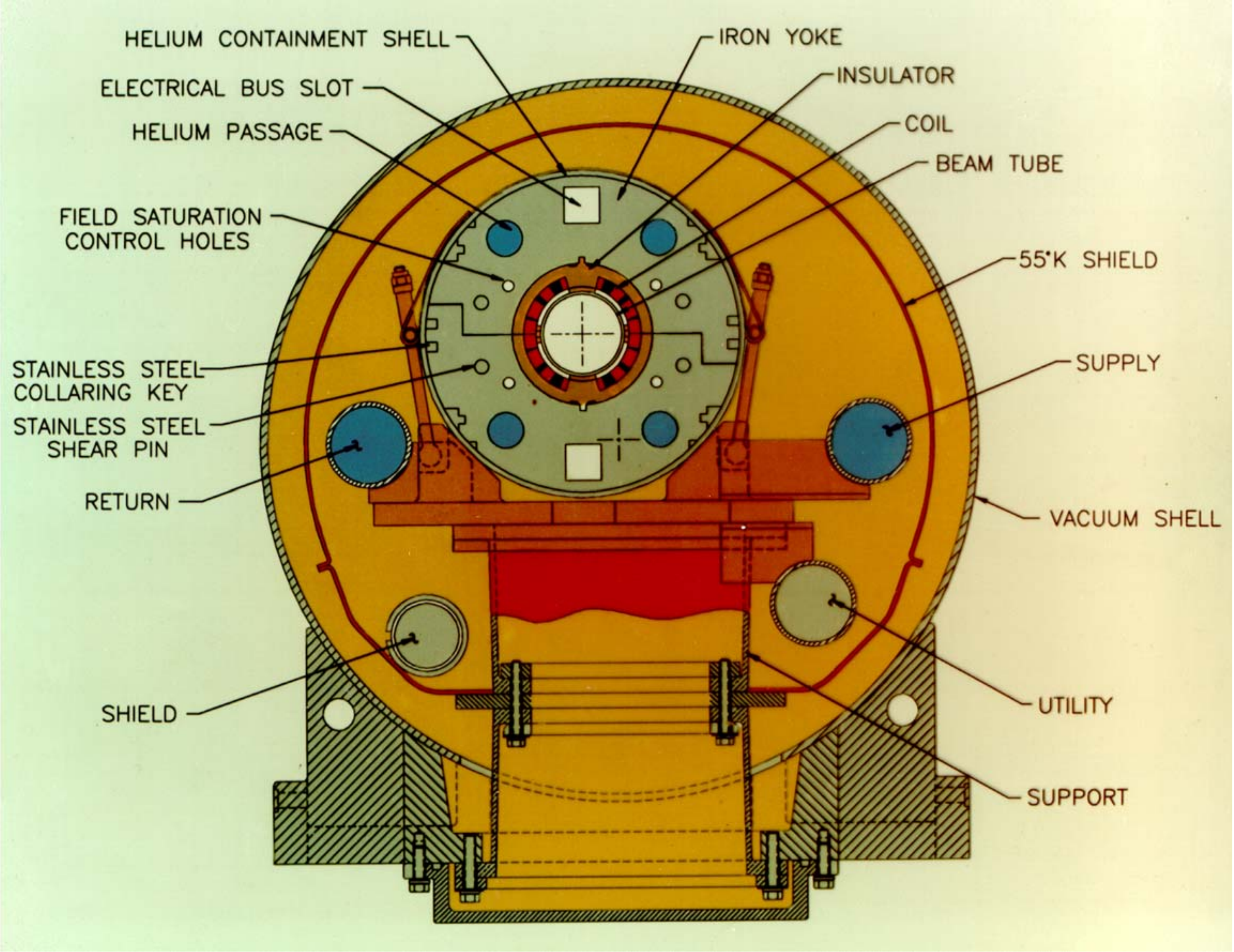


224
Justierung
Adjustment
Aufhängeband für
Strahlungsschild
Suspension band
for shield
Aufhängeband für
Magnet
Suspension band
for magnet
Strahlungsschild
Radiation shield
Stangen für Quer-
stabilisierung
Rods for lateral
stabilisation
Justierung
Adjustment
SL DIPOL HERA
SC DIPOLE HERA

RHIC

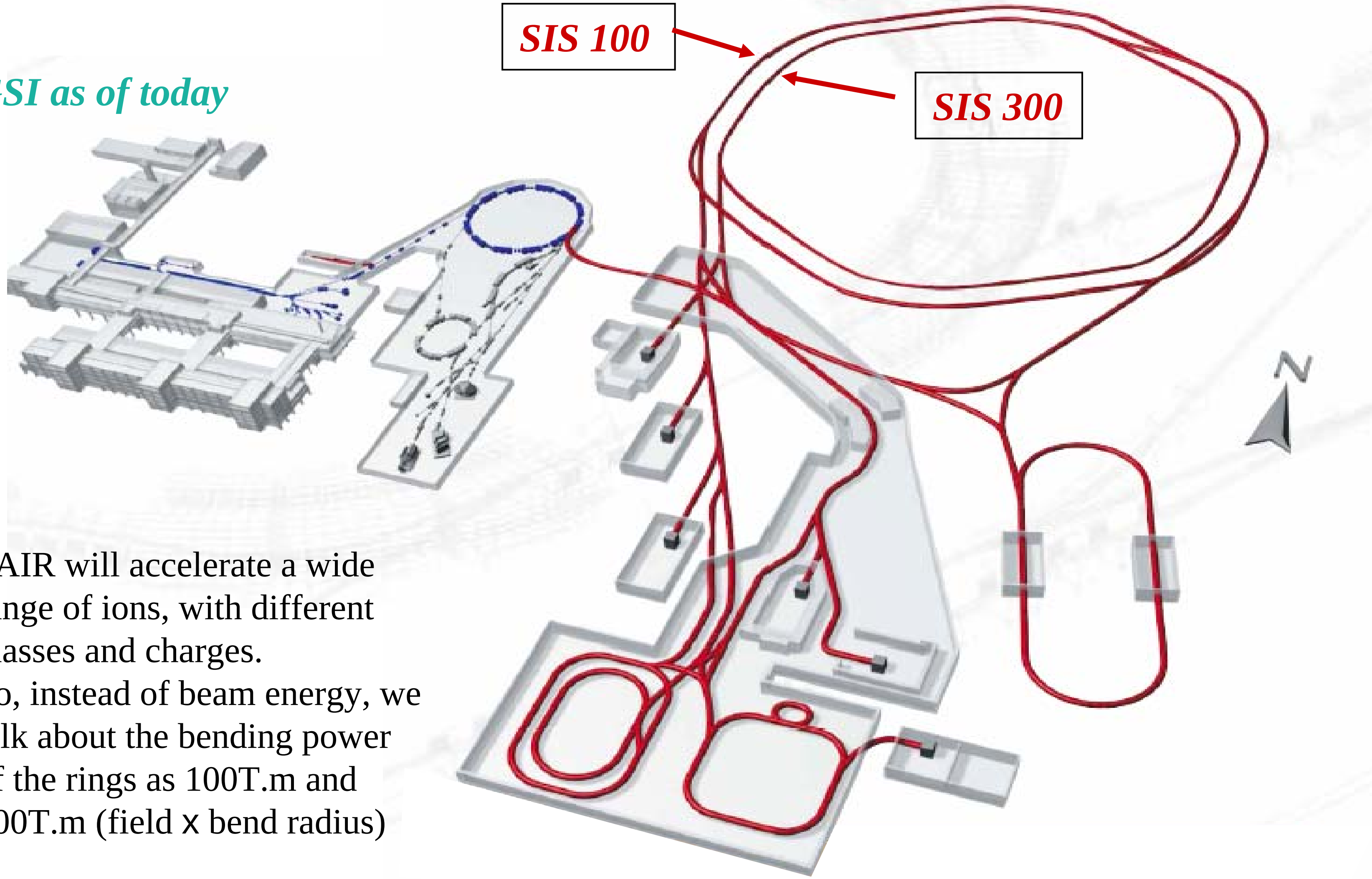


RHIC Dipole



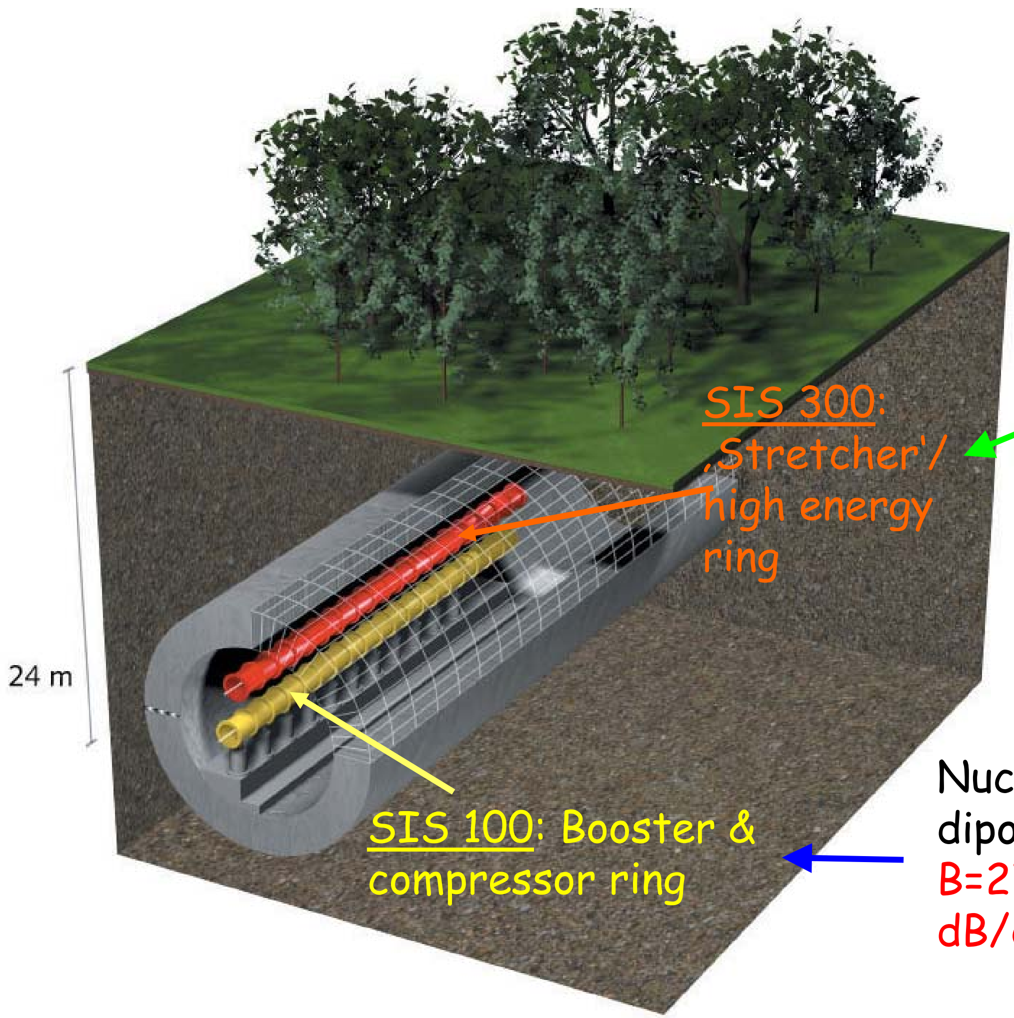
HELIUM CONTAINMENT SHELL
ELECTRICAL BUS SLOT
HELIUM PASSAGE
FIELD SATURATION CONTROL HOLES
STAINLESS STEEL COLLARING KEY
STAINLESS STEEL SHEAR PIN
RETURN
SHIELD
IRON YOKE
INSULATOR
COIL
BEAM TUBE
55°K SHIELD
SUPPLY
VACUUM SHELL
UTILITY
SUPPORT

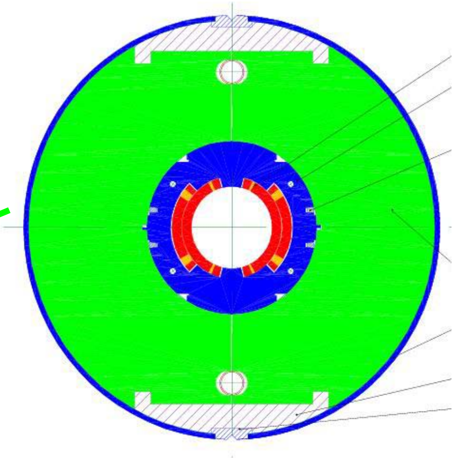
Facility for Antiproton and ion research FAIR



FAIR will accelerate a wide range of ions, with different masses and charges.
So, instead of beam energy, we talk about the bending power of the rings as 100T.m and 300T.m (field x bend radius)

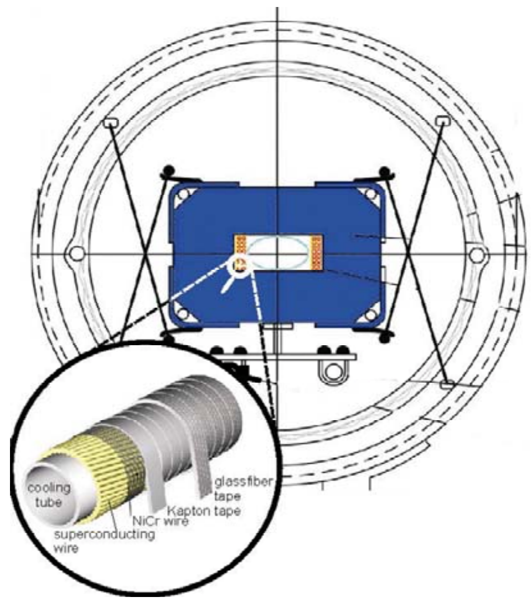
FAIR: two rings in one tunnel





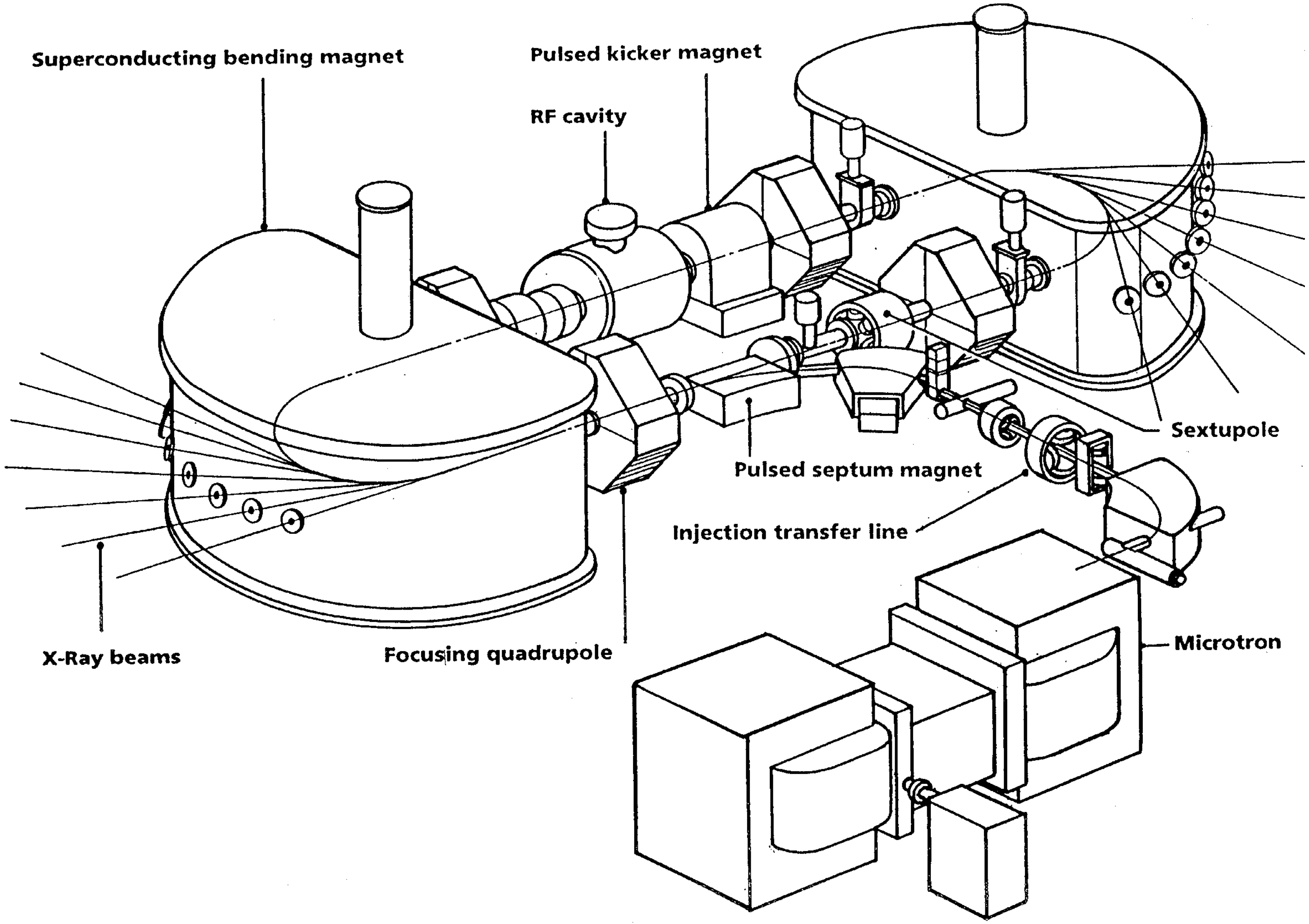
Modified
UNK dipole
6T at 1T/s

Nuclotron-type
dipole magnet:
B=2T,
dB/dt=4T/s



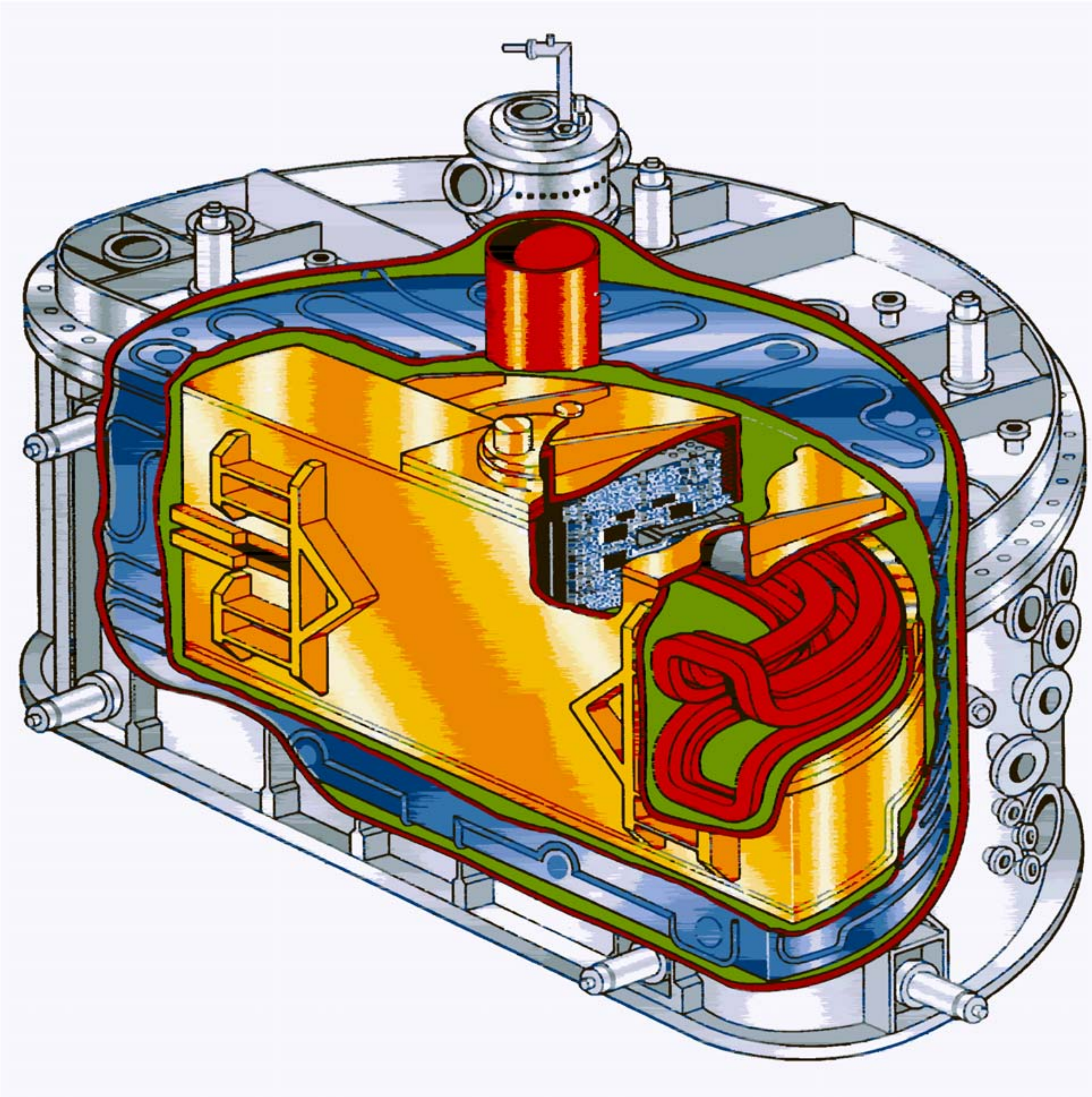
2x120 superconducting dipole magnets
132+162 SC quadrupole magnets

X-ray beams for microchip lithography:
the compact electron storage ring Helios



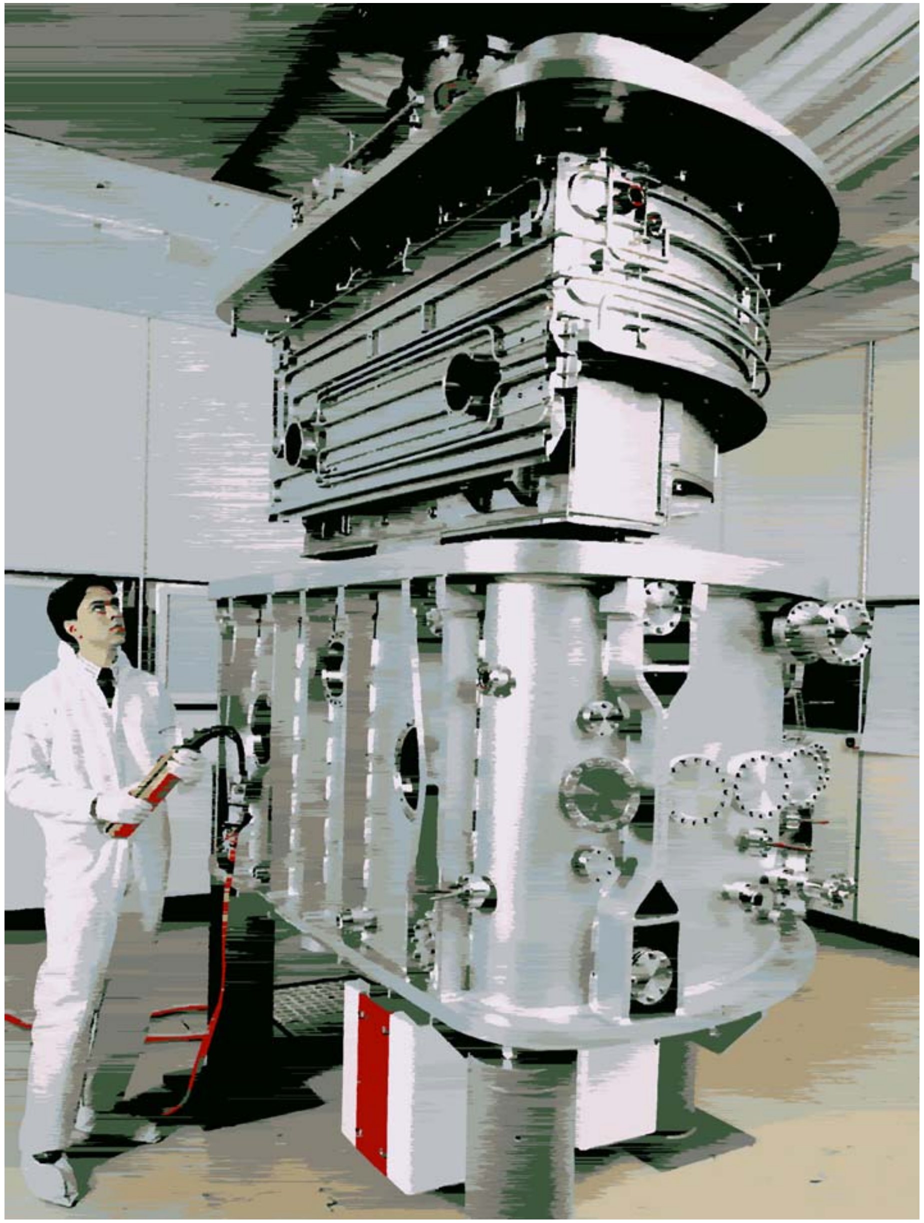
Helios

superconductivity
⇒
compact size
⇒
transportability



Helios dipole

- bent around180°
- rectangular block coil section
- totally clear gap on outer mid plane for emerging X-rays (12 kW)



Helios dipole assembly

ultra clean conditions because UHV needed for beam lifetime